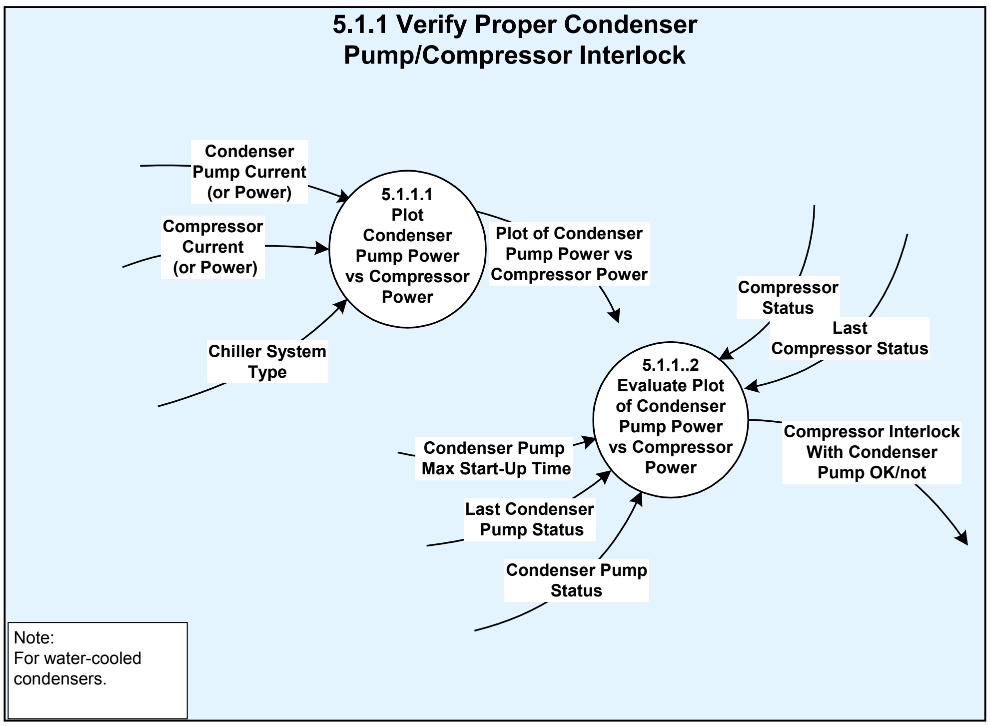
CALIFORNIA ENERGY COMMISSION

Final Report Compilation for

Pattern Recognition-Based Fault Detection and Diagnostics



TECHNICAL REPORT

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CALIFORNIA ENERGY COMMISSION

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Program's final report and its attachments are intended to provide a complete record of the objectives, methods, findings and accomplishments of the Energy Efficient and Affordable Commercial and Residential Buildings Program. This attachment is a compilation of reports from Project 2.5, *Pattern Recognition Diagnostics*, providing supplemental information to the final report (Commission publication #P500-03-096). The reports, and particularly the attachments, are highly applicable to architects, designers, contractors, building owners and operators, manufacturers, researchers, and the energy efficiency community.

This document is one of 17 technical attachments to the final report, consolidating five research reports from Project 2.5:

- *Task Report: Select Diagnostics for Automation* (Feb 2001)
- *Task Report: Select Pattern-Recognition Techniques* (Feb 2001)
- *Task Report: Implement and Test Techniques* (Dec 2001)
- *Automated Diagnostics: Software Requirements Specification* (Jul 2003)
- *Evaluation of Energy Impact of Faults* (May 2003)

The Buildings Program Area within the Public Interest Energy Research (PIER) Program produced this document as part of a multi-project programmatic contract (#400-99-011). The Buildings Program includes new and existing buildings in both the residential and the nonresidential sectors. The program seeks to decrease building energy use through research that will develop or improve energy-efficient technologies, strategies, tools, and building performance evaluation methods.

For the final report, other attachments or reports produced within this contract, or to obtain more information on the PIER Program, please visit www.energy.ca.gov/pier/buildings or contact the Commission's Publications Unit at 916-654-5200. The reports and attachments, as well as the individual research reports, are also available at www.archenergy.com.

Abstract

Project 2.5, *Pattern Recognition Diagnostics.*

Led by Battelle with participation by Architectural Energy Corporation, pursued the automation of proven diagnostic methods that were manually exercised by an expert engineer using short-term data collection. The manual methods were embodied in Architectural Energy Corporation's ENFORMA® diagnostic software.

- The research team selected several diagnostic problems associated with chillers, boilers, cooling towers, and pumps, since other projects within the program were focused on air handlers, economizers, and VAV boxes,
- Review of the visual diagnostic process for these components indicated that the best automation method would be to use rule-based methods.
- A complete specification for the automation process was produced and a limited demonstration in prototype software was completed illustrating the efficacy of this approach. Field testing was not possible because of a lapse in co-funding in the second year of the project.

This document is a compilation of five technical reports from the research.

PNWD-3321

Task Report for the

Energy Efficient and Affordable Small Commercial and Residential Buildings Research Program

a Public Interest Energy Research Program
sponsored by the California Energy Commission

Project 2.5 – Pattern-Recognition Based Fault Detection and Diagnostics

Task 2.5.1 - Select Diagnostics for Automation

Version 2

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Contents

1 Executive Summary

This report is on Task 2.5.1 - Select Diagnostics for Automation of Project 2.5 - Pattern-Recognition Based Fault Detection and Diagnostics. The project focuses on automating the diagnostic methods developed by Architectural Energy Corporation (AEC) for use with the ENFORMA software. This report presents the methodology and results of the process of selecting building systems for development of automated diagnostics. These diagnostics will be based on the diagnostic methods made available in AEC's ENFORMA software and related documents.

The process used for selecting systems is based on the subjective judgment of the three lead investigators for the project. The process was based on examination of available data on system use in California and on the professional experience of the investigators. Factors explicitly recognized in this process include:

- Potential Usefulness/Impact, consisting of
  - ✓ Prevalence of system in California
  - ✓ Availability of measured data required
  - ✓ Frequency of fault occurrence
  - ✓ Ease of corrective action

- Technical Difficulty/Risk, consisting of
  - ✓ Effectiveness of the ENFORMA diagnostic method based on past experience
  - ✓ Technical difficulty and development cost

The assessment led to selection of two major systems for development of automated diagnostics:

- *boilers and*
- *chillers*.

Several additional systems were identified as desirable candidates for automation if time and resources permit including them in the project. They include: cooling towers, Dx cooling units, heat pumps, zones, and other air distribution equipment/systems. These additional promising candidates will be reassessed for automation of diagnostics as more information regarding the cost and difficulty of development emerges from Task 2.5.2 – Select Pattern Recognition Techniques and as additional information is collected on the prevalence of systems in California and frequency of failures in specific systems. This draft report will be revised when sufficient new information becomes available to warrant revisions to the systems selected or to firm these decisions by issuance of a final version of the report.

2 Purpose of This Task Report

Project 2.5 focuses on automating select diagnostic procedures previously developed and disseminated as part of Architectural Energy Corporation's ENFORMA software. ENFORMA assists with planning data collection, initializing loggers used for short-term data collection, processing and plotting collected data, and interpreting the data. ENFORMA provides a powerful set of features for filtering and plotting data in various ways to reveal operation characteristics and problems of building equipment, which a knowledgeable investigator can use to identify and diagnose operation and performance problems. To extend usability of these diagnostic tools, ENFORMA also provides a set of sample plots that represent particular sorts of equipment behavior that can be used by investigators to identify and diagnose building-equipment performance problems. It also includes a set of example applications to a variety of buildings, systems, and equipment. The diagnostic process used with ENFORMA is primarily one of visual identification of parameter values and patterns in the data plots. The purpose of this project is to automate that fault identification process to make it faster to implement and usable by a larger (possibly less engineering trained) set of users including building operators, field service technicians, as well as building engineers, commissioning providers, energy service providers, and researchers.

The purpose of this report is to document Task 2.5.1 Select Diagnostics for Automation. This task represents the first step in selecting equipment and systems for which to automate fault detection and diagnosis from the set of equipment and systems available in ENFORMA. The report provides a description of the selection process, results of applying it, and key data used in selecting building systems and equipment for which to automate diagnostics.

3 Selection Process

3.1 Overview of the Selection Process

The ENFORMA software contains approximately 150 diagnostic plots and procedures. A table summarizing all the ENFORMA diagnostics is included as an appendix to this report. The selection process involved six primary steps:

- Developing familiarity with the fault detection and diagnostics in ENFORMA
- Collecting and analyzing data on the prevalence of systems and equipment in California (in collaboration with Project 6.1)
- Developing evaluation criteria
- Categorizing ENFORMA methods and systems/equipment
- Assessing system/equipment categories with respect to evaluation criteria
- Presentation of results.

Because the evaluation presented in this draft report was based largely on the subjective judgment of the three primary investigators for this task plus data from the Commercial Buildings Energy Consumption Survey (CBECS) database, we propose to obtain further opinions regarding the prevalence of equipment/system types in California and frequency of failures from a small sample of building service practitioners working in the California market. After collecting this additional information, the conclusions of this draft report will be reviewed and revised, if necessary, and a revision to this report will be prepared and submitted.

As Task 2.5.2 Selection of Pattern Recognition Techniques progresses, the evaluation of technical difficulty and risk will also be reassessed and adjustments made, if necessary, to the selections presented in this report.

This report provides the research team's selections of systems and equipment upon which to focus. It also provides lists of diagnostics available for each type of system and equipment that are available from ENFORMA; however, which of the diagnostics to implement for the selected equipment and systems has not been decided yet. To do so would be premature until parts of Task 2.5.2 are performed. Therefore, selection of specific diagnostics for each equipment/system category will be presented in a future report.

3.2 Equipment/System Categories

Based on review of the diagnostics in ENFORMA (see the Appendix for a comprehensive list), we created the following major categories for evaluation:

- Economizers
- Boilers
- Chillers
- Cooling towers
- Direct expansion (Dx) cooling units
- Heat pumps
- Water-loop heat pumps
- Evaporative coolers
- Zones
- Other air distribution
- Thermal energy storage
- Humidifiers/dehumidifiers.

3.3 Evaluation Criteria

Two primary criteria were used in evaluating the existing diagnostics in ENFORMA for suitability for automation in this project: 1) the expected impact of successful automation and 2) the estimated technical risk and level of effort required to automate. These two primary decision criteria are described more completely in the subsections that follow.

3.3.1 Impact of Successful Automation

The benefits from successfully automating diagnostics are likely to be influenced by four factors that will affect deployment of the diagnostic systems and the benefits that accrue from their use. These factors are:

1. How prevalent each type of system or component to which the diagnostics apply is in California.
2. How suitable the types of systems or components are to deployment of automated diagnostic technologies.
3. How common the types of faults that the diagnostics detect are for each equipment type.
4. How severe the impacts are for the types of faults the diagnostics detect.

1. Prevalence of System/Component Types in California – Most of the diagnostics used in ENFORMA are applicable only to specific types of systems or equipment. The more common the

Table 1 - Prevalence of System Types in the California Commercial Building Stock based on data from the *1995 Commercial Buildings Energy Consumption Survey (CBECS).*

System Type	Buildings		Building Floor Area		Energy Use in Buildings with System Type		
	Number	% of Total	10^6 ft^2	% of Total	Use	10^{12} Btu	% of Total
Economizers	72,905	16.7	1,769	31.3	cooling	12.8	38.3
					heating	20.6	30.0
Boilers	34,989	8.0	1,268	22.5	cooling	NA	NA
					heating	16.6	24.2
Chillers	8,957	2.0	1,013	17.9	cooling	7.9	23.7
					heating	NA	NA
Packaged Air Conditioners	201,105	46.0	2,490	44.1	cooling	18.2	54.6
					heating	NA	NA
Heat Pumps (air-to-air and hydronic)	27,267	6.2	344	6.1	cooling	2.7	8.1
					heating	0.7	1.0
Evaporative Coolers	16,676	3.8	117	2.1	cooling	< 0.1	0.2
					heating	NA	NA
All Commercial Buildings	437,276	100.0	5,644	100	cooling	33.4	100.0
					heating	68.6	100.0

applicable equipment is in California buildings, the more opportunity there will be to realize significant impact from an automated diagnostic that monitors and diagnoses faults in that equipment. Table 1 *Prevalence of Selected Characteristics in the California Commercial Building Stock* provides estimates of the population of buildings having applicable systems and equipment. The types of systems and equipment in Table 1 are not identical to the categories identified in Section 3.2, but the data are useful to identify the predominance of certain types of equipment. These data, along with the impressions of the principle investigators are the basis for the scores for prevalence of systems in California (reported later in Table 5).

The data in Table 1 are from the 1995 CBECS, published by the U.S. Department of Energy, Energy Information Administration (EIA). Although more accurate data will be gathered as part of other projects now underway in the CEC PEIR programs, the 1995 CBECS represent the best and most up-to-date source of data on the characteristics of commercial building stock throughout the State of California that are readily available now.

Unfortunately, CBECS is not organized so that data can be reported for the State of California separately from data from other states. However, by using data for buildings whose locations have less than 4,000 heating degree days (base 65ºF) and are also located in the Pacific Census Region (which includes California, Oregon, and Washington), we are able to establish good estimates for the State of California as a whole. The intersection of the census and climatic regions includes all but the northeast corner of the state (the areas with light and medium-colored shading in Figure 1). We estimate that roughly 90% or more of California's building stock is represented by this region.

There are several other noteworthy limitations to the CBECS data. While the survey is designed to gather some detailed information about mechanical equipment used in the buildings, survey administrators and

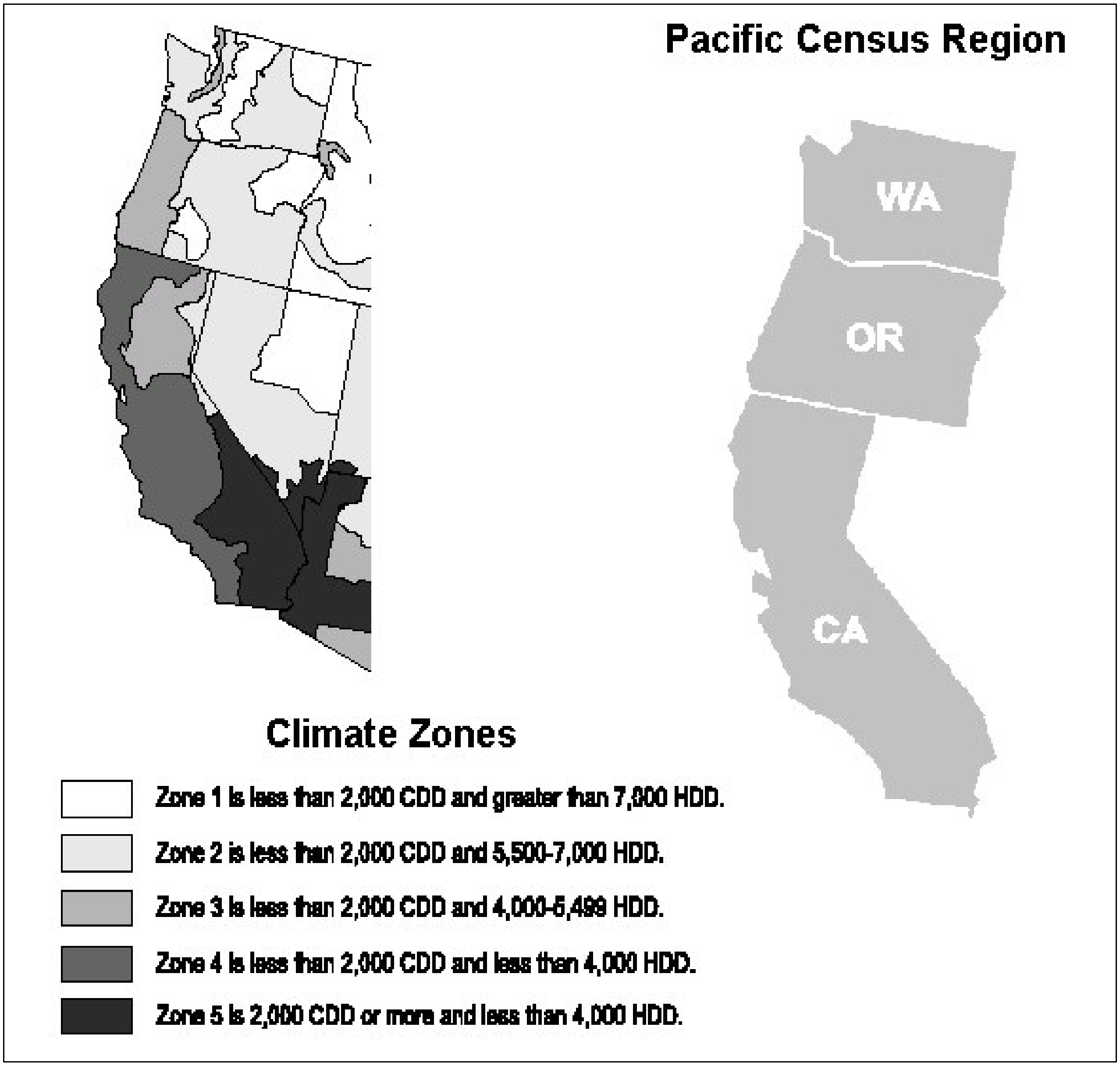

Figure 1 – The intersection of EIA Climate Zones 4 and 5 and the Pacific Census Region provides a reasonably satisfactory means to isolate California data in the CBECS sample.

(usually) survey respondents are not engineers and are not highly knowledgeable about the heating, ventilation, and air-conditioning (HVAC) systems in the buildings on which they report. As a result, data on the type of equipment present in the sample buildings may not be highly reliable, and frequently the distinctions we are most interested in were not addressed in the original survey. In addition, the statistical significance and predictive value of the CBECS data are reduced whenever the sample size is small, such as is the case with some of the less-common HVAC equipment types listed in Table 1. End-use component data (e.g., for cooling energy consumption) from CBECS are imputed rather than measured. The process of imputing end-use components has the potential for introducing additional errors not present in the whole-building consumption values, which are measured. While the 1995 CBECS contains the most recent data available, five years have passed since they were collected. Data from the past five years would be relevant and valuable for characterizing new buildings and possible trends in equipment use; however, the automated diagnostics developed in this project will be useful on equipment of all vintages in the building stock. For these and other reasons, we view the data shown in Table 1 as useful and suggestive of the prevalence and importance of the selected building characteristic, but it should not be viewed as absolute or highly precise.

Table 1 contains estimates of the numbers of buildings, their floor space, and their associated energy use for heating and cooling for buildings that use the types of equipment listed in the left-most column. The listed equipment types conform roughly with ENFORMA diagnostics that are under consideration for use in automated diagnostics. The numbers in the table serve as measures of the potential impact of the various types of diagnostics.

For example, a major question that emerges in evaluating diagnostics for chillers, cooling towers, and boilers is how important these central-plant equipment types are to overall commercial energy-use in California as compared with package HVAC equipment types. Table 1 shows that there may be only 4% (8957 buildings with chillers/201,105 buildings with packaged air conditioners) as many buildings in California that use central-plant chillers as use package cooling equipment. Most buildings that use chillers though are much larger, and the ratio of the two basic types of system is greatly increased (to about 41% = 1,013 million square feet for buildings with chillers/2,490 million square feet for buildings with packaged air conditioners) when floor area is considered. This ratio is increased even further (to about 43% = 7.9 trillion Btu for buildings with chillers/18.2 trillion Btu for buildings with packaged air conditioners) when energy consumption is considered. Buildings with package air conditioners still use more than double the energy that buildings with chillers in California use for cooling, but the energy consumed by buildings with chillers is much larger than might be realized from a casual inspection of number of buildings only. All three of these metrics—numbers of buildings, their floor area, and their energy consumption may be useful indicators of equipment importance in assessing potential impact and difficulty of achieving that impact, but their differences must be recognized.

Similar questions arise in considering the significance of heat pumps in the commercial building stock in California. Table 1 suggests that approximately 6% of commercial buildings use heat pumps for heating. From an energy consumption perspective, these buildings represent a relatively small part of the heating energy consumption picture (≈ 1%), and as a result, they have a modest contribution to energy use in California. Therefore, the potential energy impact of diagnostics for heat pumps in commercial buildings in California is much less than for systems (like roof-top packaged air-conditioning units) that represent a much larger fraction of the California building stock and space-conditioning energy use. These differences are exhibited in our assessment presented in the Results section and Table 5.

Evaporative coolers (or swamp coolers, as they are commonly called) are another equipment type that was confirmed to have low potential impact based on the CBECS data. Table 14 indicates that roughly 4% of California commercial buildings have evaporative coolers, however, these buildings tend to be quite small and to use very little energy for cooling (≈ 0.2% of the cooling energy for the commercial sector). Therefore, we would not select evaporative coolers as a target for diagnostics.

As noted earlier, the data do not show possible current trends toward more use of certain, hopefully more efficient, types of equipment. However, our judgment as the investigators is that the greatest impacts will result from focusing on the types of equipment currently predominate in the building stock. If we succeed in bringing automated diagnostics to existing equipment, new equipment will likely readily adopt automated diagnostics in the future.

Furthermore, because residential air-conditions and heat pumps are based on the same fundamental technology as commercial air-to-air heat pumps and packaged air-conditioners, diagnostics developed for commercial units might be directly (or with slight modification) applied to residential units. Therefore,

Table 2 - Prevalence of System Types in the California Residential Building Stock based on data from the *1997 Residential Energy Consumption Survey* (RECS).

System Type	Buildings		Building Floor Area		Energy Use in Buildings with System Type		
	Number	% of Total	10^6 ft^2	% of Total	Use	10^{12} Btu	% of Total
Packaged Air Conditioners	3,081,619	26.8	5042	32.5	cooling	13.2	79.0
					heating	NA	NA
Heat Pumps (air-to-air and hydronic)	295,641	2.6	380	2.4	cooling	0.9	5.3
					heating	1.3	0.6
All Residential Buildings	11,484,357	100	15,508	100	cooling	16.7	100
					heating	219.7	100

impacts for these types of units might extend into the residential sector, increasing the impact of diagnostics developed for the equivalent commercial systems. Table 2 contains estimates of the numbers of residential buildings, their floor space, and their associated energy use for packaged air conditioners and heat pumps for residences based on the *1997 Residential Energy Consumption Survey (RECS)*. The numbers in the table serve as indicators of the potential impact of the various types of diagnostics. The data in Table 2 show that:

- ✓ Package air conditioners are used in 27% of the total residential building stock
- ✓ Packaged air conditioners represent 79% of the residential energy-use for cooling
- ✓ Heat pumps represent only about 2.5% of cooling systems used in California residences.

From this, we can conclude that if diagnostic technology for commercial package units could be transferred to residential units, the potential impacts for this diagnostic technology could roughly double compared to the impacts from application to commercial units only (based on nearly equal use of energy by package commercial and residential air conditioners). On the other hand, even considering heat pumps in both the commercial and residential sectors, too few heat pumps are prevalent in California for diagnostics for heat pumps to have a significant impact compared to diagnostics for other system types.

To corroborate the results based on Table 1, we examined data reported by Pacific Gas & Electric (PG&E 1997 and 1999) and Southern California Edison (ADM Associates 1997). The results based on installed capacity are presented in Table 3. Although the service territory of the third largest electric utility in the state, SDG&E, is not included and the metrics are not identical to those in Table 1 (energy use in Table 1 and installed capacity in Table 3), most of the results tend to corroborate one another. Key conclusions from comparison of the results in Tables 1 and 3 include:

- ✓ Boilers represent about 38% (Table 3) of the heating capacity and 24% of the heating energy use (Table 1) in California commercial buildings.
- ✓ Package DX cooling units represent 42% of the cooling capacity and 55% of the cooling energy use.
- ✓ Chillers (centrifugal) represent 20% of cooling capacity and 24% of the cooling energy use.
- ✓ Heat pumps represent a small fraction (<10%) of the heating and cooling capacity and energy use.
- ✓ Evaporative coolers represent a very small fraction of the commercial cooling capacity and energy use.
- ✓ Economizer data are inconsistent between CBECS and the utility surveys.

2. Availability of Data – In order for an automated diagnostic capability to be deployed, some mechanism must be available for acquiring the requisite data from the monitored component or system. Potential mechanisms for deploying automated diagnostics vary from stand-alone software packages that analyze data collected by other systems to adding diagnostic logic to building automation systems to

Table 3 - Space conditioning equipment types prevalent in the PG&E and SCE service territories.

System Type	PG&E and SCE Service Territories	
Cooling	**tons**	**% of Total**
Packaged Cooling		
Packaged DX units (non-heat pumps)	2,494,736	42%
Heat Pumps	1,160,634	19%
Packaged evaporative coolers	56,090	1%
Packaged Cooling Capacity	**3,711,460**	**62%**
Built-up Cooling		
Centrifugal Chiller	1,199,500	20%
Reciprocating chiller/screw compressor	874,800	15%
Heat Pumps	18,730	0%
Other	159,900	3%
Built-up Cooling Capacity	**2,252,930**	**38%**
Total Cooling	***5,964,390***	***100%***
Heating	**10^6 Btu/h**	**% of Total**
Packaged Heating		
Gas furnace	54,971	49%
Heat pumps	3,854	3%
Unit heater	5,591	5%
Other electric heat	1,562	1%
Packaged Heating Capacity	**65,978**	**58%**
Built-up Heating		
Boilers	43,044	38%
Other	3,782	3%
Built-up Heating Capacity	**46,826**	**42%**
Total heating	***112,804***	***100%***
Economizing (SCE service territory only)	**10^3 ft^2 floor area**	**% of Total**
A/C Economizer w/2 stage cooling (fully or partially implemented)	163,737	9%
All Buildings in SCE service territory	**1,838,180**	**100%**

incorporating diagnostic processes into the logic on a computer chip in an autonomous control circuit for a package roof-top air-conditioner. Data acquisition is usually expensive and can pose a severe limitation on the feasibility of successful deployment. Building owners are often very resistant to adding any sensors that are not absolutely required for control of building equipment. Consequently, those systems whose diagnostics use mostly data for which sensors are already commonly installed are given higher ratings in our evaluation. In addition, for some systems data from sensors may be used locally for control but not generally be available for other uses. The investigators' impressions of this situation are used as the basis for our evaluation of suitability for automation in this project, with systems having greater data availability given higher ratings.

3. Frequency of Fault Occurrence – The benefits from automated diagnostics will be influenced strongly by how frequently the systems fail during routine operation. If a system fails frequently, targeting it with automated diagnostics is likely to provide greater impacts than a system that fails infrequently. In addition to failure during operation, many components are improperly installed and commissioned. In previous work, Battelle staff have found many equipment faults already present by using automated diagnostic tools. Certain HVAC components, such as economizers, are notorious for having operational and commissioning problems. As a result, we expect that the automated diagnostic tools developed in this project will prove valuable as aids in routine operation as well as in commissioning of new buildings and retro-commissioning of existing buildings. Account for both of these perspectives is taken in evaluation of this criterion, frequency of fault occurrence.

4. Significance of Malfunctions – The value of fault detection information depends on how serious the consequences are of the types of malfunction addressed by the diagnostic. Some malfunctions can damage equipment, others may seriously degrade overall building energy efficiency, while others serve only to diminish the efficiency improvements the system was designed to provide, and still others may have only small impacts on energy use and the cost of operation. This factor is used to indicate the significance of the faults that the candidate diagnostics would detect and diagnose, which would also be indicators of the savings that would result from correcting the detected problems.

5. Ease of Corrective Action – The value of fault detection information also depends on the ease and cost-effectiveness of correcting the faults. Some operational problems can be remedied through simple control system adjustments. Others may require large capital investments to correct. In every case, the decision to correct a problem is affected by the ease of correction and the cost of correction. This criterion is intended to capture these issues. The other major factor affecting the likelihood of a problem being corrected is the magnitude of the impact, which is captured in criterion 4.

3.3.2 Technical Risk/Level of Effort

The second major aspect of the diagnostic evaluation focuses on risk, as opposed to returns or impact. Given inherent uncertainties in the development process, this part of the evaluation focuses on identifying the diagnostics with the highest likelihood of successful development, accurate performance of the resulting diagnostics, and reasonable cost of development. Technical complexity, the novelty of the methods used, and the number of diagnostic problems addressed all add to technical risk. New methods potentially pose unexpected implementation problems. Until tested new methods pose risk. Automated pattern recognition has not been applied previously to building systems diagnostics, so risk is inherent in taking this new approach. Finally, the number of diagnostic problems addressed in the project increases the amount of effort required and, therefore, the cost of the project. Selecting diagnostics that are riskier and more technically challenging to automate would necessarily require greater effort and diminish the number of diagnostics that can be addressed within project scope. We are seeking to balance these factors in this selection process.

These risk factors are addressed in greater detail by the following two criteria used in this assessment:

1. How reliable and effective the diagnostics have been in identifying the fault when used manual within ENFORMA.
2. How technically complex we anticipate automation of the diagnostics for a system/equipment category to be. This criterion includes the need to handle expected uncertainty in the data for

each specific diagnostic, as well as the complexity of automating the ENFORM diagnostic method even in the absence of uncertainty in the data used.

1. Effectiveness of ENFORMA methods – If a diagnostic has not proven reliable when applied by expert users of ENFORMA at AEC, it is less likely that the diagnostic would perform well when automated. The assessment of effectiveness included in Table 3 was provided by the lead AEC investigator for this project based on AEC's experiences in using each of the ENFORMA diagnostics on a number of buildings. In addition to the success of the methods when used, the number of uses by AEC and its customers is also factored into evaluation of this criterion. Methods for which AEC has less experience are given less weight than those applied successfully in many cases.

2. Technical difficulty and development cost – Several factors (as discussed above) contribute to the technical difficulty of automating a diagnostics procedure. Among these factors is 1) the complexity of the method itself, 2) whether the automation method has been used previously on diagnostic problems and diagnostic problems in the buildings domain, 3) the intermittence or continuity of a problem when it occurs, and 4) uncertainty inherent in the data used for diagnosis. This criterion is intended to capture these factors in a rating.

3.4 Evaluation Matrix

Table 4 presents an empty copy of the matrix used to record the evaluation of the criteria presented in Section 3.3. On the left-most axis of the matrix are the major system/equipment categories from ENFORMA, which were identified in Section 3.3.1. In the second column, candidate diagnostics for automation from ENFORMA are shown for each system/equipment category. Which of these diagnostics to automate for each of the system/equipment categories selected in this task will be decided later in the project, while performing Task 2.5.2. In many cases, ENFORMA contains several plots and diagnostic assessments that are part of a single diagnostic entry in Table 4.

Evaluation criteria have been divided into two major categories—Potential Usefulness/Impact and Technical Difficulty/Risk, as discussed in Section 3.3. Under each of these major categories are the detailed criteria described in Section 3.3. In addition to the detailed criteria, an overall assessment is provided in the last (right-most) column of the matrix.

3.5 Assignment of Scores

Scores were assigned to each criterion for each system/equipment category (i.e., cell in the matrix). Scores were assigned subjectively by the three primary investigators, with each investigator first assigning scores independently of the other investigators for all cells for which the investigator felt qualified. These scores were based on individual knowledge and the data on system/equipment prevalence presented in Section 3.3.1. This scoring process was used for the investigators to develop some familiarity with the criteria and with the process of scoring. The investigators then met and developed a consensus set of scores through discussion of each cell and its related criterion as applied to each system/equipment category. These are the scores presented in Table 5. The "Overall Rating" in the right-most column was also assigned subjectively. It was not developed mathematically from the other scores but rather assigned independently except for consideration of the thinking behind assignment of the detailed scores. The detailed scoring is provided in Table 5 as information for reviewers and to document the team's thinking with respect to separate criteria.

Table 4 - Evaluation matrix showing system categories and evaluation criteria.

System Category	Diagnostics	Potential Usefulness/Impact				Technical Difficulty/Risk		Overall Rating
		1. Prevalence of System in CA	2. Availability of Measured Data	3. Frequency of Fault Occurrence	4. Ease of Corrective Action	5. Effectiveness of ENFORMA method (based on past experience)	6. Technical Difficulty and Development Cost	
Economizers	Scheduling Proper modulation Performance							
Boilers	Scheduling Hot-water-temperature control							
Chillers	Scheduling Chilled-water-temperature control Efficiency/ performance							
Cooling Towers	Interlock Temperature control							
Dx Cooling Units	Heat rejection Interlock Efficiency/ performance							
Heat Pumps	Scheduling Back-up heat Interlock Efficiency/ performance							
Water-loop heat pump	Scheduling Interlock Temperature control							
Evaporative Coolers	Humidity and temperature control Performance							
Zones	Temperature control Terminal-system operation							
Other Air Distribution	Scheduling Static pressure & fan control System performance							
Thermal energy storage	Schedule Operating modes Interactions Interlock Temperature control							
Humidifier dehumidifier	Performance							

System Category	Diagnostics	Potential Usefulness/Impact				Technical Difficulty/Risk		Overall Rating
		1. Prevalence of System in CA	2. Availability of Measured Data	3. Frequency of Fault Occurrence	4. Ease of Corrective Action	5. Effectiveness of ENFORMA method (based on past experience)	6. Technical Difficulty and Development Cost	
Economizers	Scheduling Proper modulation Performance	3	3	3	3	3	3	**1***
Boilers	Scheduling Hot-water-temperature control	3	3	2	3	3	3	**3**
Chillers	Scheduling Chilled-water-temperature control Efficiency/performance	3	3	2	2	3	3	**3**
Cooling Towers	Interlock Temperature control	3	3	1	3	3	2	**2**
Dx Cooling Units	Heat rejection Interlock Efficiency/performance	3	2	2	2	2	1	**2**
Heat Pumps	Scheduling Back-up heat Interlock Efficiency/performance	2	2	3	2	2	2	**2**
Water-loop heat pump	Scheduling Interlock Temperature control	1	2	2	2	3	3	**1**
Evaporative Coolers	Humidity and temperature control Performance	1	2	3	3	2	2	**1**
Zones	Temperature control Terminal-system operation	3	1	2	2	1	1	**2**
Other Air Distribution	Scheduling Static pressure & fan control System performance	3	2	2	2	2	2	**2**
Thermal energy storage	Schedule Operating modes Interactions Interlock Temperature control	1	2	3	1	1	1	**1**
Humidifier dehumidifier	Performance	1	1	3	3	2	2	**1**

* Economizers were given a score of 1 because of an additional criterion not applicable to the other categories. The Outdoor Air Economizer Diagnostician (OAE), developed by a team led by Battelle staff, exists, performs well, and is undergoing testing and demonstration in Project 2.4 of this program. The investigators judged the incremental value and impact of developing another economizer diagnostician would, therefore, probably be small.

Each criterion applied to each system category was scored on a scale of 1 to 3. These numerical scores corresponded to barely satisfying (1), moderately satisfying (2), and highly satisfying (3) the criterion (or

Table 6 - Results of system selection.

Automation Selection Category	Overall Rating in Evaluation	Systems in Selection Category
Will automate diagnostics	3	Boilers Chillers
Uncertain – would like to automate diagnostics if resources permit	2	Cooling Towers Dx Cooling Units Heat Pumps Zones Other Air Distribution
Will not automate diagnostics	1	Economizers (see footnote to Table 5) Water-loop Heat Pumps Evaporative Coolers Thermal Energy Storage Humidifier/dehumidifiers

simply low, medium, high). For example, system categories that receive ratings of 3 for the "Potential Usefulness/Impact" criteria have in the judgment of the investigators the potential for a large impact through widespread deployment and significant energy savings by successfully identifying a large numbers of faults that have significant energy impacts. Technical difficulty/risk ratings of 3 mean that in the judgment of the investigators automated diagnostics for this system category are relatively easy to develop and the ENFORMA methods on which they are based are highly reliable.

4 Results

The results of the evaluation are shown in Table 6. The system categories were divided into three final decision categories based on their overall rating. Systems with scores of 3 were selected for definite automation of diagnostics; systems with scores of 1 were eliminated from further consideration for automation of diagnostics; and systems with scores of 2 were placed in a category that we assign an uncertain decision. As the team develops more information in revising this report for Task 2.5.1 and in performing Task 2.5.2, one or two of the systems in this middle category may be moved to the top category for automation, if resources appear sufficient to develop automated diagnostics for additional systems, and a small number of systems may be moved to the lowest, won't automate, category. The current selections for automation are summarized in Table 6 – *Results of System Selection*.

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6 Appendix – Table of ENFORMA Diagnostics

This appendix consists of a table (Table 7) containing information on each of the diagnostics contained in the ENFORMA software. The following explains each column in the table:

Plot No. – The diagnostic plot number used in ENFORMA.

Plot Label – The diagnostic plot label used in ENFORMA

System Category – The major system categories used to characterize diagnostic capabilities in the ENFORMA literature

Diagnostic Category – The system attribute (or diagnostic descriptor) used to characterize diagnostic capabilities in the ENFORMA literature

Limitation on Applicability – Limitations on the applicability of a diagnostic to systems or equipment having the listed characteristics. The diagnostic is limited to use with systems conforming with the listed limitation.

Plot Description/Diagnostic Value – A description of the plot or its diagnostic value taken from the descriptions of diagnostic plots in the ENFORMA Help system.

Table 7 - ENFORMA Diagnostics

Plot No.	Plot Label	System Category	Diagnostic Category	Limitation on Applicability	Plot Description/ Diagnostic Value
40	Supply Air Delta T vs. Hour	Air distribution	Distribution system heat gain	Air distribution system	Determine if there are heat gains or losses along the supply ductwork.
30	Mixed Air Temperature vs. Ambient Air Temp.	Air distribution	Economizer	Economizer	Determine proper economizer operation.
81	Tmixed - Treturn vs. Tambient - Treturn	Air distribution	Economizer	Dry bulb temperature economizer	Determine if the economizer is modulating properly.
82	Tmixed - Treturn vs. Hambient - Hreturn	Air distribution	Economizer	Enthalpy economizer	Determine if the economizer is modulating properly.
97	Mixed Air Temp vs. Hour	Air distribution	Economizer	Economizer	Economizer diagnostic.
68	Direct Evap Cooler Effectiveness vs. Ambient Temperature	Air distribution	Evaporative cooler	Direct Evaporative Cooler	Observe variations in the direct evaporative cooler performance as the inlet dry bulb temperature varies.
69	Direct ECE vs. Inlet Wet Bulb Temp	Air distribution	Evaporative cooler	Direct Evaporative Cooler	Observe variations in the direct evaporative cooler performance as the inlet wet bulb temperature varies.
70	Indirect ECE vs. Dry Bulb Source Temp	Air distribution	Evaporative cooler	Indirect Evaporative Cooler	Observe variations in the indirect evaporative cooler performance as the source dry bulb temperature varies.
71	Indirect ECE vs. Wet Bulb Source Temp	Air distribution	Evaporative cooler	Indirect Evaporative Cooler	Observe variations in the indirect evaporative cooler performance as the source wet bulb temperature varies.
99	Direct Evaporative Cooler Temp out vs. Temp in	Air distribution	Evaporative cooler	Direct evaporative cooler	Observe the relationship between the outlet and inlet dry bulb temperatures across a direct evaporative cooler.
100	Direct Evap Cooler Enthalpy out vs. Enthalpy in	Air distribution	Evaporative cooler	Direct evaporative cooler	Observe the relationship between the outlet and inlet enthalpy across a direct evaporative cooler.
101	Direct Evaporative Cooler rh out vs. rh in	Air distribution	Evaporative cooler	Direct evaporative cooler	Observe the relationship between the outlet and inlet relative humidity across a direct

Plot No.	Plot Label	System Category	Diagnostic Category	Limitation on Applicability	Plot Description/ Diagnostic Value
					evaporative cooler.
144	Evaporative Indirect T Inlet-T Outlet vs. Hour	Air distribution	Evaporative cooler	Indirect evaporative cooler	Daily variations in the delta T across an indirect evaporative cooler.
145	Evaporative Indirect T Inlet-T Outlet vs. T Inlet	Air distribution	Evaporative cooler	Evaporative cooler	Relationship between the delta T across an indirect evaporative cooler and the inlet temperature.
146	Evap. Indirect/Direct TInlet-TOutlet vs. Hour	Air distribution	Evaporative cooler	Evaporative cooler	Daily variations in the delta T across an indirect-direct evaporative cooler.
147	Evap. Indirect/Direct TInlet-TOutlet vs. TInlet	Air distribution	Evaporative cooler	Evaporative cooler	Relationship between the delta T across an indirect-direct evaporative cooler and the inlet temperature.
148	Evap. Indirect/Direct TInlet-TOutlet v TInletWB	Air distribution	Evaporative cooler	Evaporative cooler	Relationship between the delta T across an indirect-direct evaporative cooler and the inlet wet bulb temperature.
149	Evaporative Direct T Inlet-T Outlet vs. Hour	Air distribution	Evaporative cooler	Evaporative cooler	Daily variations in the delta T across a direct evaporative cooler.
150	Evaporative Direct T Inlet-T Outlet vs. T Inlet	Air distribution	Evaporative cooler	Evaporative cooler	Relationship between the delta T across a direct evaporative cooler and the inlet dry bulb temperature.
151	Evap. Indirect T Inlet-T Outlet vs. T Inlet WB	Air distribution	Evaporative cooler	Evaporative cooler	Relationship between the delta T across a direct evaporative cooler and the inlet wet bulb temperature.
152	Evap. Indirect/Direct ECE v TInlet	Air distribution	Evaporative cooler	Evaporative cooler	Variations in the indirect-direct evaporative cooler performance as the inlet dry bulb temperature varies.
153	Evap. Indirect/Direct ECE v TWB ambient	Air distribution	Evaporative cooler	Evaporative cooler	Variations in the indirect-direct evaporative cooler performance as the inlet wet bulb temperature varies.
154	Evap. Indirect/Direct TOutlet v TInlet	Air distribution	Evaporative cooler	Evaporative cooler	Outlet and inlet dry bulb temperatures across a direct-indirect evaporative cooler.
31	Relative Humidity vs. Hour	Air distribution	Humidifier (or dehumidifier)	Humidifier or dehumidifier	Determine proper operation of the humidifier
32	Humidity Ratio Humidified Air vs. Humidity Ratio Supply Air	Air distribution	Humidifier (or dehumidifier)	Humidifier or dehumidifier	Determine proper operation of the humidifier
17	Heating Air Flow vs. Hour	Air distribution	Scheduling, static pressure & fan control	Air distribution system	Determine proper heating supply fan operation.
18	Supply Air Flow vs. Hour	Air distribution	Scheduling, static pressure & fan control	Air distribution system	Determine proper fan operation.
79	Total Heating Supply Fan Power vs. Hour	Air distribution	Scheduling, static pressure & fan control	Dual duct	Determine the schedule of the hot deck air distribution system fan and variations in the hot deck supply fan power.
80	Total Cooling Supply Fan Power vs. Hour	Air distribution	Scheduling, static pressure & fan control	Dual duct	Determine the schedule of the cold deck air distribution system fan and variations in the cold deck supply fan power.
48	Static Pressure vs. Hour (Variable Air Volume Systems	Air distribution	Static pressure & fan control	VAV systems with static pressure control	Determine the proper operation of the VAV fan controls.
52	Supply Fan Power vs. Hour	Air distribution	Static pressure & fan control	Air distribution system	Determine the schedule of the air distribution system supply fan and magnitude of the variations in the air distribution

Plot No.	Plot Label	System Category	Diagnostic Category	Limitation on Applicability	Plot Description/ Diagnostic Value
					system supply fan power.
53	Return Fan Power vs. Hour	Air distribution	Static pressure & fan control	Return fan	Determine the schedule of the air distribution system return fan and magnitude of the variations in the air distribution system return fan power.
54	Exhaust Fan Power vs. Hour	Air distribution	Static pressure & fan control	Exhaust fan	Determine the schedule of the air distribution system exhaust fan and magnitude of the variations in the air distribution system exhaust fan power.
96	Supply Fan Power vs. Flow	Air distribution	Static pressure & fan control	VAV or DDVAV	Checking the validity of power and / or flow measurements.
98	Return Fan Power vs. Supply Fan Power	Air distribution	Static pressure & fan control	Return fan	Determine if the return fan properly tracks the supply fan.
41	Static Pressure vs. Cooling Air Flow	Air distribution	Static pressure and fan control	VAV systems with static pressure control	Determine the proper operation of the VAV fan controls.
42	Static Pressure vs. Heating Air Flow	Air distribution	Static pressure and fan control	VAV systems with static pressure control	Determine the proper operation of the VAV fan controls.
156	Supply Air Temp. - Mixed Air Temp. vs. Hour	Air distribution	System performance	Air distribution system	Temperature difference across the cooling (and heating, if present) coils throughout the day.
157	Supply Air T - Mixed Air T vs. Supply Air Flow	Air distribution	System performance	VAV	Temperature difference across the cooling (and heating, if present) coils as the supply air flow varies.
2	Heating vs. hour	Air distribution	Temperature control	Dual duct system	Shows the daily heating profile for the hot deck of a dual duct air distribution system.
23	Cooling Air Temperature vs. Ambient Air Temperature	Air distribution	Temperature control	Cooling supply air reset on ambient	Determine proper operation of cooling supply air temperature reset controls.
24	Heating Air Temperature vs. Ambient Air Temperature	Air distribution	Temperature control	Central heating coil; no terminal heating	Determine proper operation of the control of heating air supply temperature reset on outside air.
25	Supply Air Temperature vs. Zone Air Temp.	Air distribution	Temperature control	Cooling supply air reset on zone air	Determine proper operation of the control of supply air temperature reset on zone air.
26	Supply Air Temperature vs. Return Air Temp.	Air distribution	Temperature control	Cooling supply air reset on return air	Determine proper operation of the control of supply air temperature reset on return air.
28	Supply Air Temperature vs. Hour	Air distribution	Temperature control	Multiple-zone system	Determine how the cold deck supply air temperature varies throughout the day.
29	Heating Supply Air Temperature vs. Hour	Air distribution	Temperature control	Multiple-zone system	Determine how the hot deck supply air temperature varies throughout the day.
34	Zone Supply Air Temp vs. Hour	Air distribution	Terminal system operation	1) Dual duct and multizone systems2) VAV with zone mixing dampers and reheat	Determine proper operation of zone mixing dampers.
35	Zone Air Velocity vs. Hour	Air distribution	Terminal system operation	1) Constant volume2) VAV mixing boxes3) Fan-powered boxes with reheat	Determine if the zone is receiving sufficient air flow.
4	Hot Water Supply Temp vs. Ambient Temp.	Boiler	Hot water temperature control	Boiler	Determine proper operation of the control of hot water supply temperature reset on outside air.
5	Hot Water Delta T vs. Ambient Air Temp.	Boiler	Hot water temperature control	Boiler	Determine proper operation of the boiler.
92	Total Boiler Stage Power vs. Ambient Temp	Boiler	Hot water temperature control	Boiler	Determine how the boiler electrical demand modulates in response to ambient

Plot No.	Plot Label	System Category	Diagnostic Category	Limitation on Applicability	Plot Description/ Diagnostic Value
					temperature.
49	HW Pump Power vs. Hour	Boiler	Scheduling	Boiler	Determine the schedule of the hot water supply pump.
91	Total Boiler Stage Power vs. Hour	Boiler	Scheduling	Boiler	Determine how the boiler electrical demand varies throughout the day.
102	Hot Water Circulation Pump Pwr vs. Ambient Temp	Boiler	Scheduling	Boiler	Determine if the hot water circulation pump is operating according to the ambient temperature schedule.
103	Hot Water Circulation Pump Pwr vs. Hour	Boiler	Scheduling	Boiler	Determine the schedule of the hot water circulation pump and magnitude of the variations in the hot water circulation pump power.
7	Total Cooling vs. Hour	Chiller	CHW temperature control	Chiller	Determine proper operation of the control of ~~hot chilled~~ water supply temperature reset on outside air.
22	Chilled Water Supply Temperature vs. Ambient Air Temperature	Chiller	CHW temperature control	Chiller	Determine proper chilled water temperature control.
62	Chilled Water Delta T vs. Hour	Chiller	CHW temperature control	Chiller	Observe variations in the chiller delta temperature throughout the day.
133	Chilled Water Supply vs. Hour	Chiller	CHW temperature control	Chiller	Hourly variation in the temperature of the chilled water supplied to the load throughout the day.
51	Total Condenser Pump Power vs. Ambient Temp	Chiller	Heat rejection	Water cooled condensers	Determine if the condenser pump power is related to ambient temperature.
50	CHW Pump Power vs. Hour	Chiller	Scheduling	Chiller	Determine the schedule of the chilled water supply pump.
45	Compressor Power vs. Ambient Air Temp.	Chiller, DX cooling plant	Performance	Mechanical cooling	Determine if cooling plant compressor is able to 1) modulate in response to outdoor temperature fluctuations and 2) meet the existing cooling loads
10	Mechanical Cooling vs. Hour	Chiller, DX cooling plant	Scheduling, Performance	Mechanical cooling	Determine if the cooling equipment 1) is turning off during unoccupied times and 2) is able to meet the existing cooling loads.
165	Cooling Tower Fan Power vs. Chiller Condenser Pump Power	Cooling tower	Interlock	Cooling Tower	Determine if the cooling tower fans are properly interlocked with the chiller condenser pump
164	Cooling Tower Fan Power vs. Hour	Cooling tower	Scheduling, Temperature control	Cooling Tower	Schedule of the cooling tower fan, Magnitude of the variations in the cooling tower fan power.
38	Clg. Tower Range vs. Hour	Cooling tower	Temperature control	Cooling tower	Observe variations in the cooling tower range throughout the day.
39	Clg. Tower Range vs. Ambient Temp	Cooling tower	Temperature control	Cooling tower	Observe how the cooling tower range varies with the ambient temperature.
57	Cooling Tower Approach vs. Ambient Wet Bulb Temperature	Cooling tower	Temperature control	Cooling Tower	Observe variations in approach as wet bulb temperature varies.
58	Clg Tower Approach vs. Ambient Temp	Cooling tower	Temperature control	Cooling Tower	Observe variations in approach as the ambient dry bulb temperature varies.
59	Clg. Tower Fan Power vs. Ambient Temp	Cooling tower	Temperature control	Cooling tower	Observe variations in the cooling tower fan usage as the

Plot No.	Plot Label	System Category	Diagnostic Category	Limitation on Applicability	Plot Description/ Diagnostic Value
					ambient dry bulb temperature varies.
60	Clg. Tower Pump Power vs. Ambient Temp	Cooling tower	Temperature control	Closed loop cooling tower with dedicated circulation pump	Observe variations in the cooling tower pump usage as the ambient dry bulb temperature varies.
61	Cooling Tower Sump Temperature vs. Ambient Wet Bulb Temperature	Cooling tower	Temperature control	Cooling Tower	Observe variations in the cooling tower sump temperature as the ambient wet bulb temperature varies.
111	Range vs. Ambient Wet Bulb Temp	Cooling tower	Temperature control	Cooling tower	Observe how the cooling tower range varies with the ambient temperature.
112	Cooling Tower Fan Power vs. Sump Temp	Cooling tower	Temperature control	Cooling tower	Determine if the cooling tower fan is cycling to properly maintain sump temperature.
64	Condenser Approach vs. Ambient Wet Bulb Temp	DX cooling plant	Heat rejection	Evaporative condenser	Observe the approach temperature of evaporative condensers as the wet bulb temperature varies.
65	Condenser Approach vs. Ambient Temperature	DX cooling plant	Heat rejection	Evaporative condenser	Observe variations in approach as the ambient dry bulb temperature varies.
66	Condenser Fan Power vs. Ambient Temp	DX cooling plant	Heat rejection	DX Cooling	Observe variations in the condenser fan usage as the ambient dry bulb temperature varies.
67	Condenser Sump Temp vs. Ambient Wet Bulb Temp	DX cooling plant	Heat rejection	Evaporative condenser	Observe variations in the evaporative condenser sump temperature as the ambient wet bulb temperature varies.
105	Compressor Power vs. Supply Fan Power	DX cooling plant	Interlock	DX Cooling	Determine if the compressor is properly interlocked with the supply fan.
106	Condenser Pump Power vs. Compressor Power	DX cooling plant	Interlock	DX Cooling	Determine if the condenser pump is properly interlocked with the compressor.
107	Condenser Fan Power vs. Compressor Power	DX cooling plant	Interlock	DX Cooling	Determine if the condenser fan is properly interlocked with the compressor.
104	Compressor Power vs. Hour	DX cooling plant	Scheduling	DX Cooling	Determine the schedule of the compressor and magnitude of the variations in compressor power.
63	Condenser Fan Power vs. Hour	DX cooling plant	Scheduling, Interlock	DX cooling	Determine the schedule of the condenser fan and magnitude of the variations in the cooling system condenser fan power.
109	Condenser Fan Power vs. Sump Temp	DX cooling plant	Scheduling, Operating modes	Evaporative Condenser	Determine if the evaporative condenser fan is cycling to properly maintain sump temperature.
110	Condenser Fan Power vs. Hour	DX cooling plant	Scheduling, Operating modes	DX cooling	Determine the schedule of the condenser fan and magnitude of variations in the condenser fan power.
56	Ambient Temperature vs. Hour	General	Ambient temperature	None	Shows the daily ambient temperature profiles for the monitoring period.
83	Heat Pump Backup Power vs. Source Temp	Heat pump	Backup heat	Air-air heat pump	Determine how the heat pump backup heat modulates in response to source temperature.
84	Heat Pump Backup Power vs. Hour	Heat pump	Backup heat	Air-air heat pump	Determine when the heat pump backup heat is being used.
155	Source Fan Power vs.	Heat pump	Cycling, Performance	Air-air heat pump	Observe the source fan

Plot No.	Plot Label	System Category	Diagnostic Category	Limitation on Applicability	Plot Description/ Diagnostic Value
	Ambient Temp				staging.
85	Heat Pump Source Fan Power vs. Compressor Pwr	Heat pump	Interlock	Air-air heat pump	Determine if the source fan is properly interlocked with the heat pump compressor.
87	Heat Pump Source Pump Power vs. Compressor Pwr	Heat pump	Interlock	Air-air heat pump	Determine if the source pump is properly interlocked with the heat pump compressor.
72	Single Zone Heat Pump Power vs. Source Temp	Heat pump	Performance	Heat Pump	Determine how the heat pump modulates in response to source temperature.
73	Single Zone Heat Pump Power vs. Zone Temp	Heat pump	Performance	Air-air heat pump	Determine how the heat pump modulates in response to zone temperature
89	Heat pump Power vs. Ambient Temp	Heat pump	Performance	Air-air heat pump	Determine how the heat pump modulates in response to ambient temperature.
86	Heat Pump Source Fan Power vs. Hour	Heat pump	Scheduling	Air-air heat pump	Determine the schedule of the heat pump source pump and magnitude of the variations in the heat pump source pump power.
88	Heat Pump Source Pump Power vs. Hour	Heat pump	Scheduling	Water source heat pump	Determine the schedule of the heat pump source pump and magnitude of the variations in the heat pump source pump power.
90	Heat pump Power vs. Hour	Heat pump	Scheduling	Heat pump	Determine when the heat pump is being used.
95	SZHP Compressor Power vs. Hour	Heat pump	Scheduling	Heat pump	Determine when the heat pump is being used.
136	Cir Pmp Pwr vs. Compressor Power	Thermal energy storage	Interactions	Ice harvester systems	Determines if the circulation pump and compressor interlocks are operating properly.
134	Brine Pump Power vs. Compressor Power	Thermal energy storage	Interlock	Ice harvester systems	Determine if the brine pump and compressor are properly interlocked.
135	Cir Pmp Pwr vs. Hour	Thermal energy storage	Interlock	Ice harvester systems	For determining the ice harvester cooling delivery schedule.
132	Delta T Storage vs. Hour	Thermal energy storage	Operational modes	Thermal Energy Storage	Temperature difference between the storage inlet and outlet.
137	Chiller Temperature Inlet vs. Hour	Thermal energy storage	Operational modes	Thermal energy storage	Inlet temperature variation throughout the day, especially during the charge mode.
138	Chiller Temperature Outlet vs. Hour	Thermal energy storage	Operational modes	Thermal energy storage	Chiller outlet temperature variations throughout the day.
139	Chiller Delta T vs. Hour	Thermal energy storage	Operational modes	Thermal energy storage	Variation in the chiller temperature drop throughout the day.
141	Temperature Tank Outlet vs. Hour	Thermal energy storage	Operational modes	Thermal energy storage	Variation of the storage tank outlet temperature throughout the day.
142	Temperature Storage Outlet vs. Hour	Thermal energy storage	Operational modes	Thermal Energy Storage	Hourly variation in the storage outlet temperature.
140	Temperature Storage Outlet vs. Ambient Temp	Thermal energy storage	Scheduling	Thermal energy storage	Correlation between ambient temperature and the storage outlet temperature.
77	Boiler delta T vs. Water Loop Inlet Temperature	Water loop heat pump	Backup heat	Water loop heat pump	Determine if the boiler is properly responding to variations in the water loop inlet temperature.
78	Cooling Tower Range vs. Water Loop Inlet Temp	Water loop heat pump	Heat rejection	Water loop heat pump	Cooling tower response to variations in the water loop inlet temperature.

Plot No.	Plot Label	System Category	Diagnostic Category	Limitation on Applicability	Plot Description/ Diagnostic Value
93	SZHP Tot Unit Pwr vs. Water Loop Circ Pump Pwr	Water loop heat pump	Interlock	Water loop heat pump	Determine if the water loop circulation pump is properly interlocked with the heat pump.
94	SZHP Compressor Pwr vs. Water Loop Circ Pump Pwr	Water loop heat pump	Interlock	Water loop heat pump	Determine if the water loop circulation pump is properly interlocked with the heat pump.
75	Water Loop Cooling Tower Range vs. Boiler deltaT	Water loop heat pump	Water temperature control	Water loop heat pump	Observe the interactions between the cooling tower and boiler control.
76	Water Loop Outlet Temperature vs. Hour	Water loop heat pump	Water temperature control	Water loop heat pump	Observe the variations in the water loop outlet temperature throughout the day.
116	Total Power vs. Hour	Zone	Schedule , Terminal system operation	Fan coils	Determine fan coil schedule and magnitude of the variations in the fan coil power.
159	Baseboard Temperature vs. Zone Temp	Zone	Scheduling, Simultaneous heating/cooling	Electric baseboard heating	Response of an electric baseboard heater to variations in zone temperature
160	Baseboard Current vs. Hour	Zone	Scheduling, Simultaneous heating/cooling	Electric baseboard heating	Performance of the an electric baseboard heater throughout the day.
158	Baseboard Temperature vs. Hour	Zone	Scheduling, Temperature control	Electric baseboard heating	Performance of an electric baseboard heater throughout the day.
121	Fan Power vs. Hour	Zone	Scheduling, zone temperature control	Fan coils	Determine the schedule of the fan coil unit
33	Zone Supply Air Temp vs. Hour	Zone	Temperature control	Air distribution system	Displays how the supply temperature to the zone varies through the day.
27	Fan Coil Air Temp vs. Zone Air Temp.	Zone	Terminal system operation	Fan coils	Determine proper operation of heating fan coil unit.
47	Baseboard Delta T vs. Ambient Air Temperature	Zone	Terminal system operation	Hydronic baseboards	Determine proper operation of hydronic baseboard heating systems.
55	Radiant Panel Temperature vs. Hour	Zone	Terminal system operation	Radiant panel heating	Determine the schedule of the radiant panel heating
114	Zone Supply Air Temp vs. Zone Velocity	Zone	Terminal system operation	VAV	Determine if the VAV box and reheat system are modulating properly.
115	Zone Velocity vs. Zone Temp	Zone	Terminal system operation	VAV	Determine if the VAV box and reheat system are modulating in response to the zone temperature.
117	Total Power vs. Zone Temperature	Zone	Terminal system operation	Fan coils with backup heat	Determine how the fan coil unit and backup heat modulate in response to zone temperature.
118	Total Power vs. Ambient Temperature	Zone	Terminal system operation	Fan coils with backup heat	Determine how the fan coil unit and backup heat modulate in response to ambient temperature.
119	Backup Power vs. Hour	Zone	Terminal system operation	Fan coils with backup heat	Determine when the fan coil unit backup heat is being used.
120	Backup Power vs. Zone Temperature	Zone	Terminal system operation	Fan coils with backup heat	Determine how the fan coil unit backup heat modulates in response to zone temperature.
123	Temperature Pipe Inlet vs. Hour	Zone	Terminal system operation	Two pipe fan coils	Determine how the pipe inlet temperature varies during day.
124	Pipe Delta Temperature vs. Hour	Zone	Terminal system operation	Two pipe fan coils	Determine how the pipe delta temperature varies during day.
125	Pipe Delta Temperature vs. Tzone	Zone	Terminal system operation	Two pipe fan coils	Determine if the delta temperature varies with zone temperature.
126	Temperature HW Pipe Inlet vs. Hour	Zone	Terminal system operation	Four-pipe fan coils	Determine how the pipe inlet temperature varies during day.
127	HW Pipe Delta Temperature vs. Hour	Zone	Terminal system operation	Hydronic heating	Determine if the pipe delta temperature varies during day.

Plot No.	Plot Label	System Category	Diagnostic Category	Limitation on Applicability	Plot Description/ Diagnostic Value
128	HW Pipe Delta Temperature vs. Zone Temperature	Zone	Terminal system operation	Four-pipe fan coils	Determine if the delta temperature varies with zone temperature.
129	Temperature CHW Pipe Inlet vs. Hour	Zone	Terminal system operation	Four-pipe fan coils	Determine how the pipe inlet temperature varies during day.
130	CHW Pipe Delta Temperature vs. Hour	Zone	Terminal system operation	Four-pipe fan coils	Determine if the pipe delta temperature varies during day.
131	CHW Pipe Delta Temperature vs. Zone Temperature	Zone	Terminal system operation	Four-pipe fan coils	Determine if the delta temperature varies with zone temperature.
36	Zone Temperature vs. Hour	Zone	Zone temperature control	None	Determine if proper room temperature is being maintained..
37	Zone Temp. vs. Inlet Temp	Zone	Zone temperature control	Air system	Determine the stratification of the zone air.
122	Fan Power vs. Zone Temperature	Zone	Zone temperature control	Fan coils	Determine how the fan coil unit modulates in response to zone temperature fluctuations.

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Task Report for the

Energy Efficient and Affordable Small Commercial and Residential Buildings Research Program

a Public Interest Energy Research Program
sponsored by the California Energy Commission

Project 2.5 – Pattern-Recognition Based Fault Detection and Diagnostics

Task 2.5.2 - Select Pattern-Recognition Techniques

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Contents

1 Executive Summary

This is the second task report for Project 2.6 – Pattern-Recognition-Based Fault Detection and Diagnostics. The objective of this project is to develop automated diagnostics for building systems using pattern recognition techniques as the basis for automation. The diagnostics themselves will be derived from diagnostic techniques developed by Architectural Energy Corporation (AEC) for use with their ENFORMA software. In the first task report, we reported on the selection of boilers and chillers as the primary components on which to focus this project. Cooling towers were added afterwards because of their importance to the performance of many chiller-based systems. This task report provides an overview of pattern-recognition techniques that may be applicable in detecting and diagnosing operational problems and discusses their potential for application to building systems. The specific techniques that will be used in the prototype tools developed in this project will be selected in Task 2.5.3 after promising candidate techniques are tested.

Pattern recognition can be defined as "the association of an observation to past experience or knowledge" (Kennedy 1998). Pattern recognition processes can be divided into two major types—classification and estimation—both of which are applicable to the fault detection and diagnostic problems in buildings. Classification is a process of applying one of a finite set of labels to an observation; e.g., classifying the cooling tower approach temperature as *normal* or *abnormal*. Estimation is the process of applying one of a potentially infinite set of numerical labels to an observation; e.g., the cooling tower approach temperature is 8.3°F. Classification techniques can provide information in classes that map directly into conclusions or actions. Estimation is relevant when numerical precision or high resolution is required. Both classes of methods should prove valuable in automating fault detection and diagnosis.

The review of pattern-recognition techniques is organized around three major types of approaches or models used for pattern recognition—*fixed models, parametric methods*, and *nonparametric methods*— plus a set of generic techniques referred to as *data preprocessing*, which can be used with any of these three types of approaches. The distinctions between the three major approaches can be blurry, and pattern-recognition applications can use these techniques in various combinations and hybrid forms.

Fixed models are used where the underlying process is well understood and equations are available that adequately represent the behavior of the system. The term *fixed models* is used because all of the parameters in the model are fixed, having been defined at the outset of execution of the pattern-recognition process.

Parametric methods offer a second approach that can be used where some conceptual understanding of system behavior exists but that understanding is insufficient to create a complete or acceptably accurate model. The term *parametric* is used because the parameters (or variables) necessary to characterize system behavior are specified based on prior knowledge. Models of this type are classified as *parametric* rather than *fixed* because some aspects of the models (e.g., values of coefficients) are determined empirically rather than based on *a priori* knowledge.

In contrast with fixed and parametric methods, *nonparametric models* are derived almost exclusively from empirical data representing past behavior of the system to be modeled, hence they can be characterized as *data-driven* methods. Nonparametric methods are suitable where the structure of the problem and the relationships among parameters cannot be defined based on prior knowledge; where they can, parametric methods are usually simpler and more effective. Nonparametric methods can be effective with very large and complex pattern-recognition problems, even when the underlying processes are not adequately understood to create fixed or parametric models. Therein lies their major advantage over fixed and parametric models, which are limited in application to problems that lie well within the limits of human comprehension. Nonparametric methods require *training data.* As a consequence, where little or no empirical data are available—as when commissioning a new built-up HVAC system—data-driven methods may not be appropriate.

Data *preprocessing* is used in some form with most pattern-recognition approaches to make the systems more efficient to develop and more effective when deployed in the field. Data preprocessing is performed using a collection of crosscutting techniques that may be applicable with fixed-model, parametric, and nonparametric approaches. Data preprocessing may be applicable to both training data used during development of the pattern-recognition application and to the data streams that a pattern-recognition application monitors during operation. The purpose of data preprocessing is to simplify the data inputs to the system and to increase the strength and clarity of the signal relative to the noise in the data. Data preprocessing can involve the use of a variety of techniques to manipulate the input data. The usefulness of these various techniques is highly problem dependent. Common techniques include averaging values, applying thresholds or filters, normalizing data, and combining correlated variables. Data preprocessing is an important step that can often mean the difference between a system that performs well and a system that performs poorly.

Selection of pattern-recognition techniques is largely an empirical process—some view it as an art. The process is highly iterative and involves applying selected techniques, testing their performance, and selecting the one that best meets the need to explain variations in the data but subject to other constraints. Selecting a model usual involves a trade-off between performance characteristics such as accuracy, memory requirements, training time, and execution speed. Often a simple model (such as linear regression) is applied to the problem and then used as a baseline with which to compare the performance of other models.

Under a broad definition of the term *pattern recognition*, there is a range of techniques that appear to be capable of supporting useful fault detection and diagnostic capabilities for building systems. In many respects, the problems of pattern recognition for building systems fault detection and diagnostics appear less challenging than many other pattern-recognition problems with which approaches reviewed in this report have shown good success.

Favorable attributes of this problem are the industry's mature understanding of the underlying science and well-developed engineering methods. The available cause-and-effect models of system behavior can enable the pattern-recognition problem to be simplified and solutions made more robust. Other favorable attributes of our problem are the small number of variables required and lenient response-time requirements. The major unfavorable attribute of the problem is the potential lack of adequate training data under some deployment scenarios—in particular with new buildings and newly installed diagnostic systems, especially for diagnostic approaches that rely on models of faults themselves.

The wealth of first principles-based models in the building-systems domain suggests that fixed or parametric models will provide the most promising approaches. However, past efforts to correlate these first principles-based models with measured building performance suggest that some tuning of these models will be required for most systems. The need for free parameters to accomplish this tuning would argue for use of parametric methods rather than fixed models. Although, nothing in this review argues strongly for focusing on nonparametric approaches, such as neural networks, it would be premature to exclude them from further consideration. There are clearly some usage scenarios and important sub-problems in which the training data would likely be adequate for use of such methods.

Final selection of algorithms will necessarily be based on specific attributes of the detection and diagnostic problems. Proceeding under other project tasks are activities that will lead to final selection of the detailed diagnostics. Final work on selecting pattern-recognition techniques awaits completion of those tasks, particularly algorithm testing in Task 2.5.3. Documentation of the final pattern-recognition technique selection decisions will be included in the task report on laboratory testing of algorithms, Task 2.5.3 Implement and Test Techniques.

2 Purpose of This Task Report

This is the second task report for a project whose object is to develop pattern-recognition techniques to detect and diagnose faults in the operation of building systems. The first task report documented the selection of the building systems to be addressed by these techniques. Boilers and chillers were selected as the primary components to be used in technique development. Cooling towers were added because of their importance to chiller performance in many systems. This second task report reviews available approaches and pattern-recognition techniques that may be applicable in detecting and diagnosing operational problems that are common in the selected components.

This report provides only a preliminary, high-level assessment of the suitability of pattern-recognition techniques to fault detection and diagnostic problems. Because Boilers, chillers, and cooling towers are each subject to multiple types of faults, the project scope comprises multiple diagnostic "subproblems." The most effective pattern-recognition techniques may vary among these subproblems. More detailed documentation and discussion of the final selection of pattern-recognition techniques will be included in the third task report, where findings can be based on tested techniques rather than entirely on paper studies.

3 Pattern-Recognition Techniques

This section provides an overview of pattern-recognition methods and techniques that may be applicable to fault detection and diagnostics for building systems.

3.1 Pattern Recognition Defined

For purposes of this project and report, we will use a rather broad definition of the term *pattern recognition*. Pattern recognition has been defined as "the association of an observation to past experience or knowledge." (Kennedy 1998) Pattern recognition has been an active area of research in the fields of psychology and neurophysiology for several decades. Humans excel at certain types of very complex pattern-recognition tasks. For example, consider the ease with which we recognize a face or the voice of a famous singer. Then contrast that ease with the daunting task of understanding the processing that goes on in the human mind or replicating that process in a computer-based device.

Some pattern-recognition tasks have been successfully automated using computer technology, and successful applications have been developed in such fields as manufacturing, marketing, medicine, and finance. Automated pattern-recognition procedures offer a number of advantages over reliance on humans to perform the same tasks. Computer-based systems can improve speed, provide continuous monitoring where only periodic monitoring is otherwise feasible, eliminate tasks that humans find tedious, substitute for human experts where they are scarce or too costly to use, and offer superior analytical capabilities for certain types of operations. An example of this later advantage would be in identifying the optimal time to service or replace air filters (while accounting for fan power) as opposed to relying on a fixed time interval or a predefined static pressure threshold.

Interest in pattern-recognition techniques has increased with the advent of very large databases—so called *data warehouses*. *Data Mining* is a term that has been used in marketing and a number of other fields for the process of extracting useful information from large datasets using pattern-recognition techniques. Other fields use such terms as *automatic discovery* and *exploratory agents* to describe what is essentially the same process. We use the term *pattern recognition* for these processes throughout the remainder of this report.

For most readers, the phrase "automated pattern recognition" probably conjures images of an actual graphical plot of data that is then interpreted graphically. While useful pattern-recognition applications probably could be developed that function by interpreting graphic images, the focus of discussions in this report is on methods that—while analogous to matching patterns in visual representations—accomplish the same thing mathematically inside a computer.

Pattern recognition processes can be divided into two major types—classification and estimation—both of which are applicable to the fault detection and diagnostic problems in buildings. Classification is a process of applying one of a finite set of labels to an observation; e.g., the cooling tower approach temperature is *normal* (or *abnormal*). Estimation is the process of applying one of a potentially infinite set of numerical labels to an observation; e.g., the cooling tower approach temperature is 8.3°F. While some define pattern recognition to include only classification, we include both classification and estimation in our definition. The reason for this is that estimation is clearly relevant to the larger problem of developing systems that perform automated fault detection and diagnostics for buildings.

3.2 Overview of Pattern-Recognition Techniques

This review of pattern-recognition techniques is organized around three major types of approaches—fixed models, parametric methods, and nonparametric methods—plus a set of generic techniques referred to as *data preprocessing*, which can be used with any of these three types of approaches.

The distinctions between the three major approaches can be blurry, and pattern-recognition applications can use these techniques in various combinations and hybrid forms. The reader is encouraged to view the three types of approaches as providing a useful way of organizing this discussion, and not as incompatible or entirely distinct methodologies.

3.2.1 General Issues

The core activity involved in creating an automated pattern-recognition capability involves building a system that accepts inputs and returns outputs. The inputs might include information about the systems (e.g., capacities, power requirements, numbers of cells, and control sequences for a cooling tower) and monitored data streams (e.g., sump temperature and electrical current to the tower). The outputs might include status information (e.g., that the tower approach, range, and power consumption are normal).

We refer to the system that accepts inputs and returns output as a *model*. Of course, software that performs automated pattern recognition would consist of more than just a computer model of the subject system's behavior. The software would require an interface to manage inputs, an interface to convey output to the user (or other entity capable of taking the requisite action), and, particularly in the case of estimation algorithms, logic to interpret model results. For example, a model might predict that under current operating conditions, the cooling tower approach temperature should be 8.5°F. At the same time, direct measurement of the actual temperatures might show the approach to be 11°F. Program logic (in addition to the model) would be needed to compare the observed temperatures to the model output, infer that a fault is present, and originate an appropriate message or signal to initiate corrective action. Figure 3-3.1 illustrates the process and needed software components graphically.

The focus of this discussion is on the models—whether fixed, parametric, or nonparametric—and not on the related software components that may be necessary to interpret results based on model output. While these other components may be necessary parts of a functioning system, they are peripheral to the core methodological decisions, which are the focus of this review.

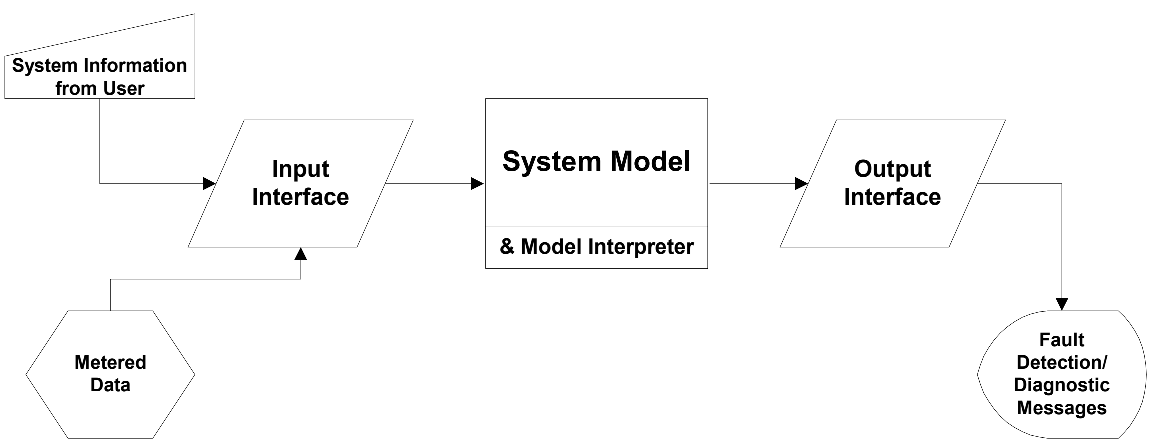

Figure 3-3.1 Conceptual Model of Diagnostic System

3.2.2 Fixed models

The first category of approaches we review is called fixed models, which represents the simplest and most straightforward pattern-recognition approach. Fixed models are used where the underlying process is well understood and equations are available that adequately represent the behavior of the system. The term *fixed models* is used because all of the parameters in the model are fixed, having been defined at the outset of execution of the pattern-recognition process. Most fixed models can be readily translated into pattern-recognition applications using common procedural programming methods.

An example of a pattern-recognition problem amenable to solution using fixed models is fault detection for air-side economizers. A model of correct economizer operation can readily be constructed based on conventional system design and outside-air damper control logic. Comparisons of model inputs of room thermostat, and outside-air and mixed-air temperatures can be used to construct a system capable of classifying economizer status as either OK, providing excessive outside air, or providing insufficient outside air under a wide variety of conditions. This approach was used in the economizer and outdoor-air diagnostic procedure in the Whole-Building Diagnostician (WBD) developed at PNNL

Expert systems are a particular type of fixed model, and are important to mention because of their potential application to building systems. Expert systems are created through interviews with human experts. Knowledge is elicited by a "knowledge engineer" and then formulated as a series of logical statements. The computer-based expert system uses the resulting "knowledge base" and software that embeds a component referred to as an "inference engine" to reason about the subject domain.

The major impediment to use of fixed models in most fields is that many pattern-recognition problems are not well-enough understood and adequately expressed in suitable form; i.e., as equations, algorithms, or available knowledge bases. Expert systems are time consuming to create, and issues related to uncertainty of inputs and confidence levels of outputs can pose significant impediments to their use, particularly where high levels of reliability are required.

Inadequate theory and equations make the use of fixed models very limited in such applications of pattern recognition as voice or character recognition—two applications that have enjoyed good success using other pattern-recognition approaches. However, fixed models offer a promising approach for many fault detection and diagnostic problems in buildings. In the buildings domain, both engineering theory and practice are well developed, and equations and algorithms capable of modeling system performance with adequate accuracy are readily available.

3.2.3 Parametric Methods

Parametric methods offer a second approach that can be used where you have some conceptual understanding of how to predict system behavior but that understanding is insufficient for you to create a complete or acceptably accurate model. The term *parametric* is used because the parameters (or variables) necessary to characterize system behavior are specified based on prior knowledge. Models of this type are classified as *parametric* rather than *fixed* because some aspects of the models (e.g., coefficients) are defined empirically rather than based on *a priori* knowledge.

An example of a parametric model for building systems can be found in ASHRAE/IESNA Standard 90. For many years, Standard 90 has used a parametric model that estimates building envelope loads for demonstrating compliance. The parameters in this simplified model where defined based on prior knowledge, but large numbers of computer simulations were used to tune the parametric model.

While there are a variety of ways to develop parametric models, linear regression is probably the most common and straightforward. Regression analysis is a statistical technique for fitting equations to (most often) empirical data. It can be used to readily develop mathematical models for estimating the behavior of systems for which there is empirical data describing past behavior. Identifying the parameters (i.e., the independent variables in the resulting regression model) is a key step in successful use of parametric methods. Knowledge of the structure of the problem and relationships among parameters is extremely helpful in developing robust parametric models that will perform well even under conditions that are not well represented in the original data. For example, knowing that the heat flow through a building envelope assembly varies directly with the assembly's area and inversely with its effective R-value is structural knowledge about the problem that is helpful in building an effective model.
An example application of parametric methods to pattern recognition might involve a system that monitors chiller efficiency and detects performance degradation. Chiller efficiency can be predicted using fixed models based on standard engineering algorithms that use inputs of rated COP and manufacturers data representing off-design performance characteristics. However, such fixed models might not yield the necessary accuracy for continuous monitoring purposes. A variety of factors may cause installed performance to differ from design performance, such as sensor placement or calibration, simplifications inherent in the engineering algorithms, pipe losses, or a large number of other conditions unique to the particular chiller or its installation. Regression analysis could be applied to measured data from the chiller, and the resulting coefficients could them be used to construct an empirical-based parametric model of chiller efficiency. In effect, this strategy would create a "tuned" model of chiller performance. This model would likely better match "normal" chiller performance than would the fixed-model alternative, and hence would likely provide a more sensitive detector of faults that cause the chiller's performance to differ from normal.

In addition to linear regression, there are two other algorithms used to develop parametric models for use in pattern recognition that warrant brief mention here—logistic regression and unimodal Gaussian. Logistic regression is a statistical algorithm that like linear regression can be used to build a model that maps inputs to outputs. Logistical regression algorithms are normally implemented using iterative methods and offer the advantage of embedding probabilities in the terms of the resulting model. However, logistic regression algorithms are not suited to problems in which input parameters are correlated, which make them ill suited to many pattern-recognition problems. Unimodal Gaussian is a relatively simple parametric algorithm, but is suitable only for classification problems. It performs well only when modeling data having Gaussian distributions. Because of its simplicity, unimodal Gaussian is a good algorithm to try first, if only to establish a useful benchmark against which to evaluate the performance of more complicated algorithms.

3.2.4 Nonparametric (data-driven) methods

In contrast with fixed and parametric methods, nonparametric models are derived almost exclusively from data representing past behavior of the system to be modeled, hence they can be characterized as *data-driven* methods. A key premise underlying data-driven methods is that the patterns in the data used to create the models (i.e., relationships between inputs and outputs) will recur in the future.

The use of nonparametric methods has grown rapidly in recent years in concert with the growth in the size of databases that organizations are creating and the increases in computational power available for analyzing these massive quantities of data. Very large datasets are being created in many fields, and nonparametric pattern-recognition methods can provide an efficient way to begin to mine the wealth of knowledge these data contain.

Nonparametric methods are suitable where the structure of the problem and the relationships among parameters cannot be defined based on prior knowledge; where they can, parametric methods are usually simpler and more effective. Nonparametric methods can be effective with very large and complex pattern-recognition problems, even when we do not fully understand and cannot model the underlying processes. Therein lies their major advantage over fixed and parametric models, which are limited in application to problems that lie well within the limits of human comprehension.

Nonparametric methods usually require a large number of example patterns of past behavior from which to build a model. These example patterns are usually referred to as *training data*. In contrast with fixed models, which represent an expression of how a system should perform based on theory (or first principles), nonparametric models do not offer any theoretical benchmark. The only basis they offer for how a system should perform is based on how it has performed. This fact has significant implications for the application of nonparametric methods to automated fault detection and diagnostics for building systems. Where little or no empirical data are available—as when commissioning a new built-up HVAC system—data-driven methods may not be appropriate. However, after successful commissioning of that HVAC system and several weeks or months of within-spec operation, continuous monitoring of the system's performance may well be a suitable application for data-driven methods. And, whether the building has been commissioned or not, with adequate training data nonparametric methods should be capable of detecting changes in system performance that occur over time.

There are many algorithms that are nonparametric in nature or that can be used nonparametrically, and there are a number of different ways these algorithms can be classified and described. The discussion in this report provides a general overview and classification of some of the more widely used algorithms available.

Parametric algorithms (such as linear regression) are included in this discussion because they can be used nonparametrically; i.e., you need not exploit knowledge of the structure and relationships among parameters to use linear regression. The decision on which algorithm to use for a given application is highly problem dependent. In most cases, there are multiple algorithms capable of producing acceptable performance, and the selection decision may depend on tradeoffs between accuracy and development time, memory, training-time, and execution-time constraints in the final software implementation, or even the personal preference of the application developer.

3.2.5 Classification of Pattern-Recognition Algorithms

Table 3-1 lists a number of widely used algorithms for addressing pattern-recognition problems and classifies them with respect to several salient characteristics. Represented in the table are a range of approaches from tradition statistical techniques, such as regression and clustering, to artificial neural[1] network techniques, such as multilayer perceptron/backpropagation. Any discussion of these algorithms and their strengths and weaknesses would readily become quite technical and is beyond the scope of this report. A glossary of terms has been included as an appendix to this report, and the reader may find the glossary helpful in understanding Table 3-1. Readers seeking more detailed information about these algorithms are referred to Kennedy et al., *Solving Data Mining Problems Through Pattern Recognition*

[1] Artificial neural networks *are analytical techniques that are so named because they function in a way that is thought to be analogous to neurobiological processes. Artificial neural networks have received considerable attention in recent years in connection with artificial intelligence and their potential for use with massively parallel computer architectures. Neural networks can be viewed as sets of interconnected nodes usually arranged in multiple layers. The nodes of the network serve as the computational elements and pass data to the other nodes to which they are connected. Neural networks can be thought of as nonparametric statistical algorithms capable of solving pattern-recognition problem for which no prior knowledge of the problem is available. Neural networks are capable of solving both classification and estimation problems. (StatSoft 2001)*

(Kennedy, 1998). That work contains a discussion of each of the algorithms in Table 3-1 and is the source for the information presented in the table.

The characteristics used in this high-level classification in Table 3-3.1 are explained briefly below.

Table 3-3.1 Pattern-Recognition Algorithms Grouped by Kernel Function

Algorithm Type	Classification/ Estimation	Parametric/ Nonparametric	Kernel Function	Boundaries (classification)	Mapping (estimation)
Linear regression	Estimation	Parametric	Line	Hyperplanes	Best fit line
Projection pursuit	Estimation	Nonparametric	Line	Hyperplanes	Linear inner product
K nearest neighbors	Estimation	Nonparametric	Euclidean norm	Piece-wise linear	Linear combination of weighted Euclidean distances
Nearest cluster	Classification	Nonparametric			
Learning vector quantization	Classification	Nonparametric			
E-M clustering	Estimation	Nonparametric			
K means clustering	Estimation	Nonparametric			
Multilayer perceptron (MLP)/Backpropagation	Estimation	Nonparametric	Sigmoid	Hyperplanes	Weighted sum of inputs passed through a sigmoid nonlinearity
Logistic regression	Estimation	Parametric			
Radial basis functions	Estimation	Nonparametric	Gaussian	Overlapping radial fields	Weighted sum of Gaussian outputs
Unimodal Gaussian	Classification	Parametric			
Gaussian Mixture	Classification	Nonparametric			
Parzen's window	Estimation	Nonparametric			
Binary decision tree	Classification	Nonparametric	Decision tree	Hyperplanes parallel to input axes	N/A
Linear decision tree	Estimation	Nonparametric			
Multivariate analysis regression splines (MARS)	Estimation	Nonparametric	Polynomial decision tree	Piece-wise polynomial	Piece-wise polynomial
General method of data handling (GMDH)	Estimation	Nonparametric	Polynomial	Piece-wise polynomial	Nonlinear spline
Hypershpere classifier	Classification	Nonparametric	Hyperspheres	Overlapping hyperspheres	N/A
See Appendix – Glossary of Terms for explanation of terms in this table.					

Classification vs. Estimation - One important way to classify nonparametric algorithms is whether they are capable of both classification and estimation or just classification. Any algorithm capable of estimation is also capable of classification; however, the inverse of this statement is not true. For example, nearest cluster, binary decision tree, hypersphere classifier, and learning vector quantization are strictly classification algorithms, which are not useful with estimation problems. Table 3-1 identifies the algorithms useful for classification vs. estimation (i.e., estimation and classification).

Parametric vs. Nonparametric – We list algorithms that can be used parametrically (i.e., to exploit prior knowledge about the structure and nature of relationships between parameters) as parametric and those that cannot be used parametrically as nonparametric. Parametric algorithms are used most effectively when data is used to "tune" free parameters in a model whose basic structure has been defined. Nonparametric algorithms do not assume there is any particular structure for the model.

Kernel Functions – Another way of characterizing algorithms is by their kernel functions or underlying computing elements. Algorithms sharing the same kernel functions tend to behave similarly. While in theory nonparametric methods are capable of use with any type of pattern-recognition problem, an algorithm will be most effective with problems whose underlying structures are compatible with the algorithm's kernel function. For example, linear problems are usually best addressed with linear algorithms, whereas problems that exhibit normal frequency distributions may be most effectively addressed with Gaussian functions. The nature of the kernel functions also determines the nature of the boundaries (in the case of classification problems) or mappings (in the case of estimation problems) that the algorithm is capable of defining.

3.2.6 Data Preprocessing

Data preprocessing is used in some form with most pattern-recognition approaches to make the systems more efficient to develop and more effective when deployed in the field. Data preprocessing is performed using a collection of crosscutting techniques that may be applicable with fixed-model, parametric, and nonparametric approaches. Data preprocessing may be applicable to both training data used during development of the pattern-recognition application and to the data streams that a pattern-recognition application monitors during operation.

The purpose of data preprocessing is to simplify the data inputs to the system and to increase the strength and clarity of the signal relative to the noise in the data. Data preprocessing can involve the use of a variety of techniques to manipulate the input data. The usefulness of these various techniques is highly problem dependent. While data preprocessing can be a highly technical topic, it is an important step that can often mean the difference between a system that performs well and a system that performs poorly. The objective of this discussion will be to provide the reader only a general description of the nature of the process and an overview of the types of techniques that are most frequently employed.

Techniques that are commonly employed in data preprocessing include averaging data values, thresholding data, reducing input space through such statistical techniques as principal component analysis, combining noncorrelated variables, normalizing data, and feature extraction. Each of these techniques is described briefly below.

Averaging data values – With time-series data, transient effects can impose noise in short time-step data received from sensors or data loggers; for example, when monitoring temperatures in ducts or piping loops. Using moving averages rather than the raw data, serves to average out fluctuations that are not really meaningful, enabling more accurate and sensitive fault detection.

Thresholding data – This technique can be used to discount or ignore inputs that are above or below some threshold, in effect removing noise due to transient effects (e.g., from equipment startup) from the signal.

Reducing input space – In some situations, there may be so much input data that identifying the signature of a problem is like looking for the proverbial needle in a hay stack. In cases of data overload, statistical techniques such as principal component analysis can identify the most meaningful data, enabling the rest to be discarded. These techniques can lead to dramatic reductions in the quantity of data that needs to be processed and to a clearer signal from the data that remains.

Combining noncorrelated variables – Knowledge of the underlying system can often be exploited to translate multiple input variables into a more concise and meaningful form before pattern-recognition algorithms are applied. For example, for a rooftop direct expansion (Dx) unit, the efficiency of the unit can be calculated from input current, supply air-flow rate, and relevant air-stream temperatures. It would constitute an easier pattern-recognition problem to identify faults by monitoring the unit's efficiency versus ambient temperature than by monitoring current, flow rate, and temperatures before and after the coil vs. ambient temperature.

Normalizing data – Normalizing (or scaling) data is often necessary to keep numerically large inputs from overwhelming numerically smaller ones. The normalization problem is similar to the problem of scaling axes on a graph to effectively display trends in the data. Sometimes nonlinear transformations are necessary (like using a logarithmic scale) in order to enable pattern-recognition algorithms to perform most effectively.

Feature extraction – Feature extraction involves exploiting knowledge about the underlying problem in order to improve the performance of pattern-recognition algorithms. An example would be recognizing vertical and horizontal lines in alphanumeric characters (as opposed to pixels in a bitmap) as part of a character recognition application. In commissioning, feature extraction might involve filtering so that only data from selected time periods are used to monitor proper operation of the outside-air damper.

3.3 Selecting Pattern-Recognition Techniques

Research has shown that various algorithms can achieve similar levels of accuracy in solving many pattern-recognition problems (Kennedy 1998). However, algorithms may vary more significantly with respect to certain practical considerations, such as execution time, memory requirements, training time, complexity of the training process, and adaptability to new data. Kennedy et al. propose the following sequence of steps when selecting appropriate algorithms for use in pattern-recognition applications.

1. First, consider any hard constraints related to the final application. If the application requires an estimation result, algorithms capable only of classification results would not be appropriate. Execution time (i.e., the time needed to generate a classification or estimation result) can also represent a hard constraint. For example, an application providing quality assurance surveillance for an industrial production assembly line might have a rigid constraint on the execution speed for the deployed system, making use of certain types of algorithms infeasible. Kennedy (1998) contains a discussion of each of the algorithms addressed in Table 3-3.1 and rates their relative performance with respect to memory requirements, training times, and execution times (see Table 3-3.2).
2. Other constraints may be less rigid than the hard constraints listed above but may still represent important design tradeoffs. Requirements related to execution speed, training time, memory requirements for model training, and expected frequency of model retraining should be defined for the proposed application, for use assessing possible performance tradeoffs related to algorithm selection.
3. If you know the form of the model based on prior knowledge, use a parametric algorithm. Parametric algorithms allow you to reduce training times by reducing the number of training parameters. The resulting model is likely to provide greater accuracy, particularly if the data available for training is not representative of the entire region of interest. Parametric algorithms have major advantages where training data are scarce or costly to obtain. Prior knowledge can also influence the selection of nonparametric algorithms, as when the nature of the phenomenon being modeled is known to be better handled by one type of kernel function than another.

4. Certain algorithms offer unique advantages related to calculating probabilities that may be useful in generating confidence measurements. For example, the Gaussian mixture algorithm inherently produces estimates of probability density functions, and in some applications these can be useful in providing guidance on how much to trust the results.

5. An alternative approach to algorithm selection is to begin with the simplest algorithm—linear regression—and shift to more complex algorithms only after the easiest method is shown to produce inadequate results. This approach has the added advantage of establishing a performance benchmark against which progress can be measured as work proceeds using more complex algorithms.

Table 3-3.2 Performance Characteristics of Patter Recognition Algorithms

Algorithm Type	Memory	Training Time	Test Time
Linear regression	Very Low	Fast	Very Fast
Projection pursuit	Low	Medium	Fast
K nearest neighbors	High	Very Fast	Slow
Nearest cluster	Medium	Medium	Med-Fast
Learning vector quantization	Medium	Slow	Medium
E-M clustering	Medium	Medium	Medium
K means clustering	Med-Hi	Medium	Med-Fast
Multilayer perceptron (MLP)/Backpropagation	Low	Slow	Very Fast
Logistic regression	Very Low	Medium	Very Fast
Radial basis functions	Medium	Medium	Medium
Unimodal Gaussian	Very Low	Medium	Fast
Gaussian Mixture	Medium	Slow-Med	Medium
Parzen's window	High	Very Fast	Slow
Binary decision tree	Low	Fast	Very Fast
Linear decision tree	Low	Fast	Very Fast
Multivariate analysis regression splines (MARS)	Low	Medium	Very Fast
General method of data handling (GMDH)	Low	Med-Fast	Fast
Hypershpere classifier	Medium	Medium	Medium
After Table 10-7 in Kennedy (1998).			

4 Pattern Recognition for Building Fault Detection and Diagnostics

The selection of pattern-recognition approaches is highly problem dependent. For that reason, we begin our discussion of the application of pattern recognition to buildings with a description of the context in which fault detection and diagnostics for buildings would be deployed.

4.1 Description of Opportunities in Buildings

This discussion is presented in two parts: 1) a discussion of the context and opportunities for buildings generally and 2) a discussion of the context and opportunities for the component diagnostics that have selected for development and demonstration in this project. This two-part approach has been used because the intent of the project is to develop diagnostic approaches that can eventually be generalized to additional building systems and components—not just those used directly in developing diagnostic approaches for this project.

4.1.1 General

This section describes some salient attributes of (or perhaps assumptions about) this building-related problem that distinguish it from others for which pattern recognition-based applications have been successfully deployed.

- Most buildings are unique. Most components or systems in buildings that would warrant fault detection or diagnostic capabilities must be understood in the context of other systems with which they interact. Solutions that offer no capability to be adapted or tuned to the building in which they operate are unlikely to have broad application.
- The fault detections and diagnostics that this work primarily targets are by nature <u>non</u>urgent, although they may prove to be costly over time and hence can be important. Major components such as chillers and boilers often have dedicated controls designed to deal with faults that could damage equipment or create dangerous situations. Other potentially serious faults from an occupant perspective, become readily apparent to occupants, such as the failure of a water heater to provide hot water.
- Particularly for early applications of pattern recognition-based diagnostic applications, reliability —and avoidance of false positive diagnoses) is considered very important. A lack of user acceptance is a potentially large impediment to successful deployment of building diagnostic systems and falsely identified problems could quickly discourage building operations from using automated diagnostics.
- An estimated half of the commercial-building floor area occurs in small buildings without on-site operating personnel. Servicing is provided by off-site personnel, who are summoned when operational problems are apparent. Under this service model, diagnostic messages that indicate the cause of the problem are probably less valuable than when operating personal are on-site and possess both the knowledge and wherewithal to implement corrective action.

There are a number of different ways that fault detection and diagnostic capabilities can be deployed. The focus of this project is on development and demonstration of these methods and not on final implementations. However, it is helpful to keep in mind the variety of ways these methods could be deployed, as deployment options can carry with them a variety of constraints and opportunities. The most conventional vehicle for deployment of automated diagnostic methods is in the software of building automation systems (also known as energy management systems). On this platform, pattern recognition-based diagnostics might represent incremental change for current products. Pattern-recognition methods can be incorporated in testing procedures used in building or system commissioning and recommissioning procedures, often done using short-term metering capabilities. Related applications might be as additions to routine servicing procedures used by equipment service personnel. Finally, diagnostic methods could be incorporated into the controllers sold with package equipment such as roof-top units or incorporated into thermostats or other control devices, that provide supervisory monitoring of a system or entire building or component monitoring via wireless link to remote sensors.

4.1.2 Project Focus

The focus for this project work is to develop and demonstrate pattern recognition-based diagnostics for boilers, chillers, and cooling towers. The selection decision was documented in the Task 2.5.1 Report as boilers and chillers. Cooling towers were added following subsequent analysis of chiller diagnostics that revealed strong advantages to addressing chillers and cooling towers jointly.

Boilers, chillers, and cooling towers are components most commonly used in central built-up systems. These systems are most often used in large commercial buildings. These buildings typically have an on-site building manager responsible for operation of the HVAC system and are more likely to have a building automation system in place than are smaller buildings. Many of the sensors necessary for automated fault detection and diagnostics may already be in place as part of these building automation systems. If fact, diagnostic tools that rely on sensors already present for control are more likely to receive early acceptance than those requiring additional sensors. The financial rewards associated with efficient operation of the buildings in terms of energy-cost savings are much greater in large buildings than in smaller ones. Central systems do not enjoy the inherent redundancy and resiliency inherent in multiple small package systems, hence there is likely more interest in preventative action in response to early fault detection to avoid untimely downtime of key HVAC components. These factors all contribute to making these systems a favorable environment for initial deployment of automated fault detection and diagnostic capabilities. Although thorough commissioning of new buildings is by no means routine, these large buildings are more likely to receive some functional testing initially to ensure that components are performing according to specification when installed.

4.2 Evaluation Relative to Technique Selection Criteria

4.2.1 Classification vs. Estimation

The distinction between classification and estimation is a distinction between selecting from a finite set of states vs. assigning a value from a continuous range. The simplest fault detection and diagnostics can be addressed as binary classification problems; e.g., is the chiller operating normally—yes or no? or is the damper stuck at its minimum outside air position—yes or no?

Estimation approaches offer the potential to convey additional information that could provide greater value to the building operator. For example, in addition to operating normally, the chiller is currently operating 3% below rated efficiency or, in addition to the outside-air damper being at minimum set position, the outside are fraction is at 18% when it should be at 100%. The estimation result provides more information from which the user (or perhaps eventually a more sophisticated computer-based diagnostician) can infer the severity of the fault, the likely consequences of continued faulty operation, and what might be the root cause of the fault.

While it may be useful to view some of the problems in buildings as classification problems, there is potential added value in approaching at least some diagnostics as estimation problems. We expect that fault detection and diagnostic systems for buildings will need to be addressed as a mix of classification and estimation problems. For some simple systems and components, classification results may be fully satisfactory. For larger and more complex systems and components, estimation results may be advantageous, if not initially in the long run because they offer greater potential for informative diagnostic results.

4.2.2 State of Knowledge of the Underlying Phenomena

An assessment of the state of knowledge of the underlying problem is important because it determines the feasibility of pursuing pattern-recognition solutions based on fixed-models or parametric algorithms as opposed to using nonparametric algorithms, which are generally more difficult to implement. There is a high level of understanding of the physics and engineering that governs the performance of all of the systems and equipment likely to be the subject of fault detection and diagnostic systems for buildings. In addition, engineering algorithms and computer models that adequately describe the performance of these systems and equipment are readily available.

Previous work, such as PNNL's outdoor-air/economizer diagnostic module in the Whole-Building Diagnostician, has used fixed models to perform fault detection and diagnostics for air-side economizers. While the system has performed well, the effort required to build the diagnostic capability was high, and because the system incorporates detailed engineering knowledge, results are not readily generalizable to other problems.

However, buildings never operate exactly the way they are expected to based on first principles. Most building systems are sufficiently complex and dependencies on weather, occupant behavior, installation conditions, and many other factors result in significant deviation from design performance. For all but the simplest building systems, variations between actual behavior and theoretical behavior are likely to be significant. Some "tuning" of models will likely be needed in most cases. As parametric approaches offer the capacity to adjust models of known form using empirical data, they are good candidates for use in this application. Fixed models may be appropriate for simple systems and those not strongly influenced by exogenous factors; such as weather and occupant behavior.

4.2.3 Availability of Training Data

Training data are usually empirical data that reveal the relationship between model inputs and outputs based on relevant conditions. Training data are necessary to tune parametric models and are essential for the creation of nonparametric models. Fault detection and diagnostic systems may be deployed under a variety of scenarios, and the availability of training data may vary widely between these scenarios. Some possible scenarios are discussed below.

Existing building scenario – The first scenario involves an existing building with months or even years of performance data that is assumed to represent "correct" (or within specification) behavior. Under this scenario, training data would be assumed to represent correct performance. It may be possible to detect Deviations from this behavior to identify when problems are occurring or that improvements have been made. The specificity of such detections limited only by the detail in the data and the models developed from it.

For approaches relying on modeling of faulty behavior itself, training data for faulty conditions is required. It is possible to identify performance such data associated with faults as they occur happenstancially. Over time, that approach could result in valuable training data for the system, but such training data would, at best, accumulate slowly and would be unlikely to be captured at all, because the association of the data representing the faulty behavior with the root cause of the fault would necessarily have to be done manually. In theory, training data could also be generated by deliberately disabling components or perturbing systems in the building. This approach is unlikely to gain wide acceptance because it would be disruptive to normal use of the building and because of the difficulty (or impossibility) of inducing some kinds of faulty behavior.

Computer simulations offer another way to create training data. However, there are at least two major challenges to this approach. First, available simulation tools are generally not designed to model faulty performance. While faulty performance can be simulated or approximated with some simulation tools, there is little guidance to be found within the technical literature on how to do this. Secondly, simulation tools rarely match actual performance closely, particularly over short time intervals. The discrepancies between the two are of comparable magnitude with the faults that an automated detection system would be designed to detect. This suggests that some tuning of the model would likely be necessary.

New building scenarios - A second scenario involves new buildings, new fault detection and diagnostic system installations in existing buildings, or existing buildings that were never been commissioned and whose performance is suspect. Under all of these scenarios, no training data would be available that represents within-spec performance. Under these conditions, the only benchmark for normal performance would need to come from first principles-based models—a severe limitation for reasons discussed above.

Manufactured component scenario - This final scenario involves a manufactured component, such as a roof-top Dx unit. A fault detection and diagnostic capability might be embedded within the unit's controller. In contrast with previous scenarios in which we assumed each build is unique, this scenario involves manufactured products, which may be produced in large quantities. A Dx unit is a somewhat simpler piece of equipment than a chiller and is far less unique than a built-up system. Under these circumstances, it may be reasonable to derive training data from other similar units.

The most plausible way for this training data to become available would be for the manufacturer to operate a unit (or a detailed computer model of the unit) under a range of faulty conditions corresponding with the scope of the fault detection system in a test facility. HVAC test facilities are capable of varying loads on a piece of equipment and subjecting it to various condenser and evaporator temperatures. Provided the training data developed this way represents the range of conditions the unit is normally expected to operate under, this scenario could yield appropriate training data to support a variety of pattern recognition-based diagnostics.

Summary - In general, limitations on the availability of training data appear to represent a potentially significant impediment to use of data-driven approaches for fault detection and diagnostics in buildings. However, there are notable exceptions, fault detection systems embedded in manufactured components being one example. In addition the Whole-Building Energy module of the Whole-Building Diagnostician developed at PNNL uses data-driven methods to identify changes in performance that are discernable at the whole-building and major-system (e.g., electricity for HVAC or gas usage) level. This tool and data-driven modeling approach it uses have proven quite effective in identifying deviations from expected behavior, albeit still limited to highly-aggregated energy consumption. This approach, however, in principle could be extended to greater levels of resolution provided the required data are available. Other Potential Constraints

For some applications, practical considerations can constrain the selection of pattern-recognition algorithms. This section reviews the requirements for building-related applications to determine if algorithm selection will likely be constrained by any of these practical considerations.

4.2.3.1 Execution Speed

Most building operational issues are not time-critical. Operational issues typically need to be addressed in days, hours, or minutes not seconds or milliseconds. Given that few building system faults would require attention in even a few minutes, it is unlikely that considerations of execution speed will impose any constraint on algorithm selection.

4.2.3.2 Memory Requirements

Memory requirements for diagnostic systems for buildings are expected to be low. This is in part a consequence of the small number of parameters that it is practical and cost-effective to monitor today. This may change in the future if installed costs for sensors can be significantly reduce, but currently few sensors beyond those required for rudimentary control are installed in most commercial buildings. While data loggers and building automation systems typically employ time steps that are measured in seconds, time-series data is usually summed and stored using much longer time steps. Memory considerations are unlikely to constrain algorithm selection due to the combined effects of using few parameters, the lack of need to store short time-step data, and low perceived value of retaining large amounts of historic data.

4.2.3.3 Frequency of Retraining

Retraining of pattern-recognition systems may be necessary with any significant new addition of training data. Retraining may be desired after retrofits or major repairs (e.g., replacement of a boiler or chiller, but the need for frequent system retraining appears unlikely. Given the anticipated modest quantities of training data, even algorithms that are slow to train should pose no problems for buildings-related systems.

5 Conclusions and Further Work on Algorithm Selection

Under a broad definition of the term *pattern recognition*, there is a range of techniques that appear to be capable of supporting useful fault detection and diagnostic capabilities for building systems. In many respects, the problems of pattern recognition for building systems fault detection and diagnostics appear less challenging than many other pattern-recognition problems with which approaches reviewed in this report have shown good success.

Favorable attributes of this problem are the industry's mature understanding of the underlying science and well-developed engineering methods. The available cause-and-effect models of system behavior can enable the pattern-recognition problem to be simplified and solutions made more robust. Other favorable attributes of our problem are the small number of variables required and lenient response-time requirements. The major unfavorable attribute of the problem is the lack of adequate training data under some deployment scenarios—in particular with new buildings and newly installed diagnostic systems.

The wealth of first principles-based models in this domain suggests that fixed or parametric models will provide the most promising approaches. However, past efforts to correlate these first principles-based models with measured building performance suggest that some tuning of these models will be required for most systems. The need for free parameters to accomplish this tuning would argue for use of parametric methods rather than fixed models. Although, nothing in this review argues strongly for focusing on nonparametric approaches, such as neural networks, it would be premature to exclude them from further consideration. There are clearly some usage scenarios and important subproblems in which the training data would likely be adequate for use of such methods.

Final selection of algorithms will necessarily be based on specific attributes of the detection and diagnostic problems. Proceeding under other project subtasks are activities that will lead to final selection of the detailed diagnostics. Final work on selecting pattern-recognition techniques awaits completion of those tasks. Documentation of the final pattern-recognition technique selection decisions will be included in the task report on laboratory testing of algorithms, Task 2.5.3 Implement and Test Techniques.

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7 Appendix – Glossary of Terms

architecture	*Architecture* refers to the basic structure of a pattern-recognition model. Training algorithms are used to tune free parameters in a pattern-recognition model. For example, k means clustering is an algorithm that can be used with nearest cluster architecture. The distinction between algorithms and architecture is subtle and is explained here primarily to clarify the use of terminology in this report.
Artificial neural networks	*Artificial neural networks* are analytical techniques that are so named because they function in a way that is thought to be analogous to neurobiological processes. Neural networks can be viewed as sets of interconnected nodes usually arranged in multiple layers. The nodes of the network serve as the computational elements and pass data to the other nodes to which they are connected. Neural networks can be thought of as nonparametric statistical algorithms capable of solving pattern-recognition problem for which no prior knowledge of the problem is available. Neural networks are capable of solving both classification and estimation problems. The multi-layered perceptron/backpropagation is a particular type of neural network that is discussed in this report.
binary decision tree	*Binary decision trees* is a type of model used for classification pattern-recognition problems in which a simple top-down tree structure is used. Binary decision trees have two branches (or leaves) below each decision node. See also *decision tree.*
decision tree	*Decision trees* are a type of model that can be used for both classification and estimation pattern-recognition problems. Use of decision trees is popular because they are relatively easy to understand. A decision tree consists of a tree-like structure in which each decision is represented by a node, no branches intersect, and final decisions are represented by the leaves (lowest level) of the decision tree. Decision trees can be divided into two type binary and linear (See *binary decision tree*).
E-M clustering	*Estimate-maximize clustering* is a nonparametric algorithm used for classification and estimation pattern-recognition problems. It easily accommodates categorical and continuous data.
Euclidean	*Euclidean* refers to something of or related to Euclidean geometry. *Euclidean* geometry is the study of points, lines, planes, and other geometric figures, using a modified version of the assumptions of Euclid (c.300 BC). The most controversial assumption of Euclidean geometry is the parallel postulate, which states that there is one and only one line that contains a given point and is parallel to a given line. Modifications of Euclid's parallel postulate provide the basis for non-Euclidean geometry.

Gaussian Of or pertaining to the *Guassian* (or Normal) distribution. The bell-shaped Guassian distribution is best characterized by its probability density function $f(x) = 1/[[2\pi\ \sigma^2)^{1/2}]\ \exp\{-(1/2)[(x-\mu)/\sigma]^2\}$, where μ is the mean of the distribution and σ is the standard deviation of x about μ.

Gaussian mixture The *Gaussian mixture* method involves fitting mixtures of Gaussian distributions to multivariate data. The mixture is the weighted sum of the individual Gaussians. This mixture can be used to approximate arbitrarily complex distributions. The parameters in the Gaussians and the weightings are determined using estimate maximization (E-M), which is an iterative process in which the objective is to maximize the likelihood that the given data points were generated by the mixture of Gaussians.

group method of data handling (GMDH) *Group method of data handling (GMDH*) is a nonparametric architecture for classification and estimation pattern-recognition problems. GMDH uses heuristic methods to simplify a polynomial-based estimation model and keep it from becoming intractably complex. The process begins with low-order polynomials, which are combined to form higher-order polynomials. Unimportant terms are removed from the equations and terms are added back to enable even higher order polynomials. The training process is terminated when successive iterations do not resulting in improvements to the estimation model.

hyperplane An *N*-dimensional construct, which divides an *N+1* dimensional space into two, much like a line (N = 1) divides a 2-dimensional space in two and a plane (N = 2) divides a 3-dimensional space in two.

hypersphere An *N*-dimensional analogy of a sphere. The surface of an N-dimensional sphere is N-1 dimensional, much like the surface of a (3-dimensional sphere is 2-dimensional.

hypersphere classifier *Hypersphere classifiers* are a type of boundary-forming classifier. Boundary-forming classifiers have binary outputs that form decision regions that designate the output class. They are trained by minimizing overall classification error rates. Hypersphere classifiers are used as the basis for some neural network algorithms which are trained using supervised learning.

K means clustering *K means clustering* is an algorithm used to define a given number of clusters from a training data set, which can then be used in classifying observations. K means clustering minimize the overall mean distances between observations in the clusters. The k means clustering algorithm can be used with radial basis functions and other cluster-based pattern-recognition architectures.

K nearest neighbors *K nearest neighbors* (KNN) is a simple architecture for pattern-recognition based on cluster analysis. The classification or estimation result is based on a selected number (K) of the closest observations in the training set, where "closeness" is based on a calculated distance metric, which is usually Euclidean. KNN is quick to train (because the entire training data set is used), but is generally reserved for low-dimensional problems and small data sets because it is very memory intensive and slow to execute.

learning vector quantization *Learning vector quantization (LVQ)* uses a nonparametric architecture identical to that of nearest cluster. It is suitable for classification pattern-recognition problems only. LVQ differs from nearest cluster in the way the model is trained. After clusters are defined using the k-means clustering algorithm, cluster centers are incrementally adjusted to minimize misclassifications using the training data, often resulting in improved model performance.

linear decision tree *Linear decision trees* are a type of architecture that can be used for both classification and estimation pattern-recognition problems. The nodes in a decision tree represent decisions. Linear decision trees represent these as inequalities of linear form that may involve multiple variables. Training of linear decision trees is more complicated than for binary decision trees and is based largely on heuristic processes.

linear regression *Linear regression* is a category of parametric modeling problems where the objective is to estimate the value of a continuous output variable from some input variables, where the relationships between the output variable and input variables is assumed to be linear. For one output variable, y, the linear regression model takes the form

$$y = c_0 + c_1 x_1 + c_2 x_2 + c_3 x_3 + \ldots + c_n x_n,$$

where $x_1, x_2, x_3, \ldots, x_n$ are the input variables, the coefficients $c_1, c_2, c_3, \ldots, c_n$ and the constant c_0 are selected to optimize the model's accuracy (usually by minimizing the sum of the squared errors) and n-1 is the number of independent variables.

logistic regression

Logistic regression creates a parametric mapping between input variables, $x_1, x_2, \ldots, x_N$ to an output y, according to the logistics function (S-shaped)

$$y = 1/[1 + \exp(-\ )],$$

where

$$= w_0 + \sum_{i=1}^{N} w_i\, x_i\, ,$$

where the w_i's are free parameters, the x_i's are the independent input variables, and N is the number of input variables. The weights are determined by minimizing what is known as the cross-entropy error for the training set,

$$E = \sum_{i=1}^{N_{training}} E_k\, ,$$

where

$$E_k = d_k \ln(1/y_k) + (1- d_k) \ln[1/(1- y_k)],$$

is known as the cross-entropy cost function, y_k is the output produced by the kth input vector, d_k is the desired output for the kth input vector, and $N_{training}$ is the number of training input vectors.

multilayer perceptron (MLP)/ backpropagation

Multilayer perceptron (MLP) is a nonparametric architecture used in with classification and estimation pattern-recognition problems. MLP is used with the backpropagation algorithm and is considered a type of artificial neural network (see *artificial neural network*). MLP consists of a network of interconnected nodes usually in multiple layers. Each node outputs a weighted sum of the nodes to which it is connected, and it is the weights of each of the nodes that represent the free parameters in the MLP models.

multivariate adaptive regression splines (MARS)

Multivariate adaptive regression splines (MARS) is a nonparametric architecture for classification and estimation pattern-recognition problems. MARS involves partitioning inputs into an n-dimensional grid. Heuristics are used to merge partitions to reduce size and complexity where doing so will not impact the accuracy of the model. Low-order polynomials are fit to the training data for each partition, but the regressions splines are constrained so as to ensure smooth transitions across partition boundaries. Because the number of initial partitions grow exponentially with the number of dimensions, MARS becomes intractable for high-dimensional problems (i.e., > 10 input parameters).

nearest cluster	*Nearest cluster* is a pattern-recognition architecture used primarily for classification problems. Nearest cluster architecture is similar to k nearest neighbors (KNN), but the training data is partitioned into clusters—see *k nearest neighbors*. *Nearest cluster* yields similar results to KNN but executes more quickly and is less memory intensive. Like KNN, nearest cluster is used mostly for small problems.
Parzen's windows	*Parzen's windows* is a nonparametric architecture for classification and estimation pattern-recognition problems and is similar to the Gaussian and Gaussian mixture architectures. The method uses weighted averages of radial Gaussian basis functions to create the probability density function model. The method is less reliable than other algorithms when used with limited training data.
projection pursuit	*Projection pursuit* is nonparametric architecture based on regression analysis. Rather than developing a regression model with a large number of dimensions, the model development process is decomposed into an iterative process that develops a series of low-dimensional regression models designed to minimize error relative to the training data set.
radial basis functions	*Radial basis functions (RBF)* is a nonparametric architecture used for classification and estimation pattern-recognition problems. With RBF, probability density functions in the model are radial Gaussian distributions. RBF models can be trained using iterative gradient descent methods or more quickly by k means clustering algorithms
Sigmoid	A *sigmoid* is an S-shaped curve, with a near-linear central response and saturating limits. Examples include the logistics function and the hyperbolic tangent (tanh).
training algorithm	*Training algorithms* or just algorithms are used to tune free parameters in pattern-recognition models. (See also *architecture*.)
unimodal	A unimodal distribution is a distribution with one mode, such as the Gaussian distribution. The mode is the value of the random variable, x, at which the probability density function peaks. A unimodal distribution has only one peak, whereas multi-modal distributions (e.g., the bimodal) have multiple peaks.
Unimodal Gaussian classifier	The unimodal Gaussian classifier is a parametric pattern recognition method that relies on the assumption that the probability distributions for input vectors for each class are Guassian. The output of the method is the probability density function of the input vector X given the class were know to be Cj. The method serves as a good benchmark for comparison of results from more complex methods.

Sources: Kennedy 1998, Lippmann 1994, StatSoft 2001, Winkler and Hays 1975.

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Task Report for the

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Project 2.5 – Pattern-Recognition Based Fault Detection and Diagnostics

Task 2.5.3 - Implement and Test Techniques

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Contents

1 Executive Summary

This is the third task report for Project 2.5 – Pattern-Recognition-Based Fault Detection and Diagnostics. It presents work to test the general rule-based approach for automating diagnostics by using it as the basis for a limited testing prototype. This testing prototype automates part of the diagnostic process for chillers in Excel using Visual Basic Applications (VBA). When run against data from actual buildings, the results are consistent with those obtained by an expert interpreting plots from AEC's *ENFORMA HVAC Analyzer*.

The tests validate that rules are effective for automating the AEC diagnostic process. The results also led to recognition of the importance of developing a method by which to detect short-term anomalous chiller behavior and to sort out what information should be presented to users and what should be filtered before display to prevent over-burdening building operators with superfluous information.

The testing software is enclosed with the report for demonstration and examination by the reader.

2 Purpose of This Task Report

This is the third task report for a project whose object is to develop software to automatically detect and diagnose faults in the operation of selected building systems. The purpose of this task is to implement and test the general approach selected for automation of the diagnostics. The purpose of this report is to describe the prototype implementation used to test the approach, to describe the associated algorithm testing and evaluation, to present some example results, and to present conclusions as they relate to using this approach for development of the diagnostic software that will be produced in this project.

3 Project Background

This report describes work from the third task in a six-part project to develop and demonstrate automated pattern recognition fault detection tools. Given the difficulty and complexity of developing fault detection and diagnostic procedures, the project objective has been to automate diagnostic procedures developed previously and used successfully by AEC with its ENFORMA software.

In the first task, diagnostics for chillers and boilers were selected for automation. Cooling towers were subsequently added to this scope due to their strong interactions with chillers.

The second task reviewed techniques from the fields of pattern recognition and data mining for use in automating fault detection and diagnostics. After review of a full range of possible techniques, including data-driven methods such as neural networks, we selected rule-based techniques as the primary approach. The primary reasons for rejecting data-driven methods was the lack of adequate training data to support use of those techniques for the particular HVAC-system related problems selected in the first task. In addition, rule-based approaches appeared well matched to the types of information available and diagnostic techniques used by AEC with *Enforma*.

Based on extensive experience of AEC staff using the ENFORMA product in conducting short-term monitoring and diagnoses for a large number of commercial building projects, the most useful and well-developed diagnostics that AEC has traditionally used with chillers, boilers, and cooling towers were documented using data flow diagrams, data dictionaries, and other written forms. These will be presented in a future report.

Part of the third task (Task 2.5.3: *Implement and Test Techniques*) is the subject of this report. This work involved implementing a set of rules for a representative part of the diagnostic process to test the general approach to automation using rules. This work was necessary to confirm relatively early in the project that the proposed rule-based approach would be feasible and effective as an automated process. The procedures that AEC and others have used with ENFORMA rely heavily on the knowledge and experience of the engineer using the *Enforma*. Confirmation was needed that those diagnostic processes would work as automated procedures. In addition, there are often large amounts of noise in metered data from buildings, and testing was needed to ensure that the planned diagnostics would perform effectively with actual building data.

Three additional tasks are to follow for this project. These tasks are

- Task 2.5.4: Implement User Interface – a task that will demonstrate an initial user interface for end users and link with software that demonstrates the initial pattern recognition algorithms.
- Task 2.5.5: Field Test – a task that will field test the prototype from the previous task and document results.
- Task 2.5.6: Implement full set of diagnostic interpretations and an expanded user interface. This task that will produce the final software deliverable containing the full set of diagnostic capabilities with improvements based on the field test under Task 2.5.5.

4 Description of Prototype Implementation and Algorithm Testing

A software prototype that implements chiller control diagnostics was developed by Stuart Waterbury in Excel VBA (Visual Basic for Applications) to test and evaluate the proposed approach for automating fault detection and diagnostics. This prototype system is designed to track and evaluate actual chilled water supply (CHWS) temperatures against the control set point. Similar work was performed using the same software environment to implement boiler hot water control diagnostics; however, the chiller version represents a more substantial and interesting problem. For that reason, this task report focuses on the chiller diagnostics, even though the hot water control diagnostics were also implemented and subjected to similar testing.

4.1 General Description of Prototype and Testing Approach

The prototype chiller control diagnostics were developed in Excel VBA in order to enable quick and flexible development, easy inspection of intermediate results, and easy visualization of data inputs and outputs. Although the eventual final implementations of these diagnostic methods will likely be designed for continuous operation, this prototype uses static building operating data previously acquired through field data collection activities. Multiple datasets were available from the extensive field work that AEC has done using ENFORMA® HVAC Analyzer. Data from five different commercial buildings with chilled water systems were selected for use with this prototype. The datasets for most of the buildings included roughly two weeks of data collected on two to three minute intervals. These data were imported into the Excel spreadsheet.

4.1.1 User Interface for Testing Prototype

Figure 1 shows the user interface screen developed for the prototype. Note that this interface is for algorithm testing, and later user interfaces for diagnostic users may bear little resemblance to this user interface. However, reviewing the interface and the example data it contains may help the reader better understand the scope and nature of the diagnostic prototype. Information appearing in the fields with white backgrounds is dynamic; areas with gray background are static. The dynamic data are organized as follows: 1) system status, 2) current performance data (i.e., values for the current time step from the original data set or data inferred directly from the original data), 3) setup data (i.e., user entered assumptions about the system and diagnostic settings), 4) current calculated values used in the diagnostic processing (mostly intermediate calculations), and 5) a log of abnormal or fault conditions identified during the current diagnostic processing period.

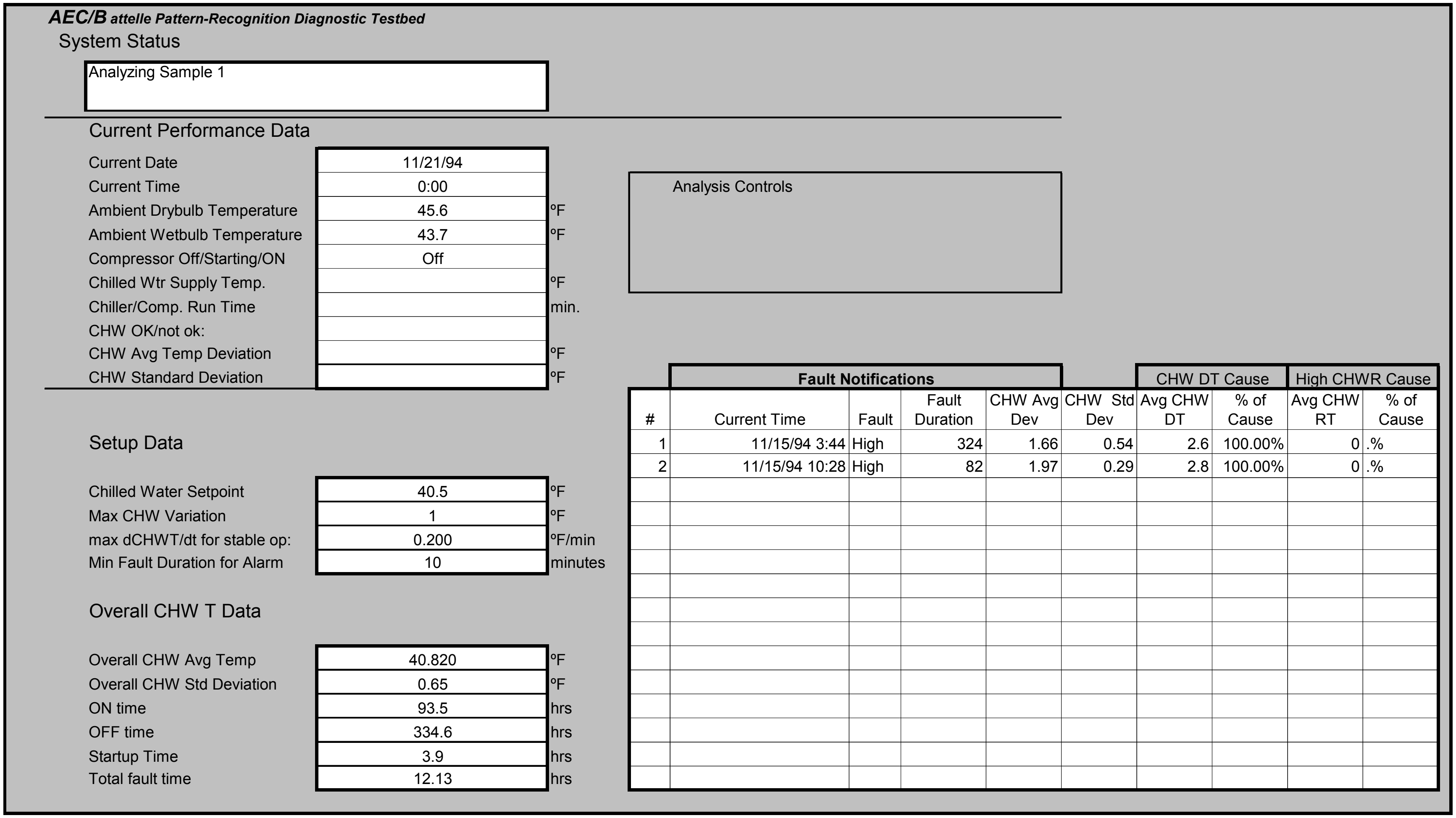

Figure 1. User Interface of Algorithm Testing Prototype

4.1.2 Diagnostic Processing

The diagnostic process embodied in the prototype can be roughly described as consisting of the following four steps:

1. Load set points and other criteria into the analysis framework.
2. Perform an initial pass through the time-series data set to determine the maximum valid chilled water (CHW) temperature difference and CHW return temperature. These values are used in evaluating some potential causes of high CHW temperature.
3. While processing the data record for each time step, determine the operating status of the chiller. Operating status is designated using the following three-category classification:
   - Off
   - Startup sequence (on but not yet at steady state)
   - On (at steady state)
4. Perform a final pass through the data set, performing the following procedure: for all records with the chiller operating in a steady-state mode,
   - Determine if CHW supply temperature is within specifications (i.e., setpoint plus or minus the specified throttling range).
   - If CHW supply temperature is not within specifications, evaluate two possible causes:

     1) excessive CHW return temperature; i.e., too large a load from the secondary (air side) cooling system

     2) inadequate CHW temperature difference; i.e., inadequate cooling provided by the chiller.

One of the functions of such a system will be to notify building operating personnel when there is a problem. Since it is normal for CHW temperatures to occasionally fall outside of the "normal" range for brief periods of time, this prototype has been designed to notify the user (in the case of this prototype, by adding a notification entry to the log) only after the fault has persisted for a set period of time. This is to prevent sending notices to the user too frequently or in the absence of a fault that required operator attention. Otherwise the operator would quickly find the system annoying, leading to the messages being ignored or the system defeated.

An important dimension of the problem of automating fault detection is to achieve an appropriate balance between system sensitivity (i.e., the ability to detect even minor faults) and immunity from falsely reporting fault conditions. While it is easy to change the various settings that determine whether conditions are out of specification or of sufficient duration for the fault conditions to be reported, determining what these settings should be is a challenge. We discuss in the Conclusions section of this report some options that warrant further evaluation as strategies for developing appropriate settings.

4.2 Scope and Functionality of Spreadsheet Implementation

As was stated previously, this prototype compares the CHWS temperature to the desired set point and generates notifications when the CHWS temperature remains out of specification for a stipulated length of time. In addition to this basic fault detection function, there are diagnostic extensions to this process that determine why the CHWS temperature may be out of specification. The following extensions were implemented:

- Difference (DT) between the chilled water return temperature and chilled water supply temperature less than represented in the design specification
- CHW return temperature too high, indicating that the load is greater than the chiller can serve.

A basic and important criterion for diagnostics automated as part of this project has been that they require relatively few, easily obtained measurements. The measurements that are currently required are:

- CHW supply temperature
- CHW return temperature
- Chiller power (or current)
- Chilled water pump power, current, or status (on/off)

More sophisticated diagnoses of the causes for out of specification CHWS temperatures might be possible with additional measurements.[1]

4.3 Diagnostic Example From Prototype

The following section shows example results generated from one of the data sets used to test this prototype. The data for this example were collected at a hospital in Newport, RI, during a particularly hot period in August 1995. During this period, the CHWS temperature occasionally exceeded acceptable limits resulting in the system being unable to maintain comfort conditions.

Figure 2 lists the setup data for this example. The CHWS setpoint was 43°F, with +/- 2°F permitted variation (or throttling range). For these test runs, the fault duration threshold was set to 30 minutes—the time that the CHWS temperature can remain of out of specification before a fault notification is generated. (Some results shown later in this example were generated with this setting changed to 10 and 125 minutes.)

Setup Data

Chilled Water Setpoint	43	°F
Max CHW Variation	2	°F
max dCHWT/dt for stable op:	0.200	°F/min
Min Fault Duration for Alarm	30	minutes

Figure 2. Setup Data

[1] Some aspects of chiller operation that aren't being evaluated currently but that could prove useful are listed below; however, adding these to our diagnostics would require additional measurements. In addition, some of these diagnostics are already being handled adequately by the chiller control system using interlocks, as they are related to safety or equipment protection.

- Low or high refrigerant pressure (requires pressure transducers integrated into the chiller)
- Flow interlocks (already part of most control systems)
- Current limiting
- Flow rates that are substantially different from design
- Chiller efficiency (requires flow meter).

Figure 3 shows a snapshot of the data at a specific point in time. As the dataset is processed, the fields in Figure 3 are constantly updated. At the time step shown, the CHWS temperature has exceed the setpoint plus throttling range by 0.2°F. The processing results displayed in this portion of the interface determines only that the CHWS temperature has exceeded the limit; other processing determines if a notification needs to be generated.

System

Analyzing Newport Data

Current Performance

Current Date	8/12/95	
Current Time	13:30	
Ambient Drybulb Temperature	77.8	ºF
Ambient Wetbulb Temperature	72.1	ºF
Compressor Off/Starting/ON	On	
Chilled Wtr Supply Temp.	45.2	ºF
Chiller/Comp. Run Time	810.0	min.
CHW OK/not ok:	High	
CHW Avg Temp Deviation	2.1	ºF
CHW Standard Deviation	0.07	ºF

Figure 3. Sample System Status

The table shown in Figure 4 lists all the notifications generated for the combination of building dataset and diagnostic settings for this data set. Included in this reporting are the time that the fault started (Current Time), the duration of the fault (Fault Duration), the deviation of the CHWS temperature from the desired set point (CHW Avg Dev), and whether the cause is due to low delta T or high CHWR temperature (CHW DT Cause).

	Fault Notifications					CHW DT Cause		High CHWR Cause	
#	Current Time	Fault	Fault Duration	CHW Avg Dev	CHW Std Dev	Avg CHW DT	% of Cause	Avg CHW RT	% of Cause
1	8/12/95 12:08	High	64	2.11	0.08	8.5	100.00%	0	.%
2	8/12/95 13:20	High	22	2.1	0.06	8.5	100.00%	0	.%
3	8/12/95 14:44	High	24	2.07	0.07	8.5	100.00%	0	.%
4	8/15/95 21:50	High	120	2.42	0.24	8.7	8.30%	54.2	91.70%
5	8/16/95 3:32	High	30	2.12	0.06	8.8	6.70%	53.9	93.30%
6	8/16/95 5:40	High	838	5.15	1.49	8.7	2.60%	57.2	97.40%
7	8/17/95 3:28	High	802	4.7	1.25	8.3	3.70%	56.7	96.30%

Figure 4. Fault Notifications

To evaluate these results, several plots are presented below.
Figure 5 shows the CHWS temperature and the notification periods for a portion of the dataset. Notice that when the allowable fault duration period is increased to 125 minutes, the shorter fault periods at the left no longer generate fault notifications.

Figure 6 illustrates potential causes of high CHWS temperature. The CHW temperature difference (CHW DT) and the CHWR temperature are plotted versus the CHWS temperature. When the CHWS temperature is between 42.5°F and 44.5°F, the CHW DT varies as the load varies. There is a similar result for the CHWR temperature; it generally ranges between 46 and 53°F. However, when the CHWS temperature increases beyond 45°F, the CHWDT plateaus at around 9°F, because the chiller cannot generate any more cooling. Since the CHW DT has reached its maximum value, the CHWR temperature rises as the CHWS rises. The data shown here are indicative of a chiller that cannot meet the load. Referring back to Figure 4, notification 6 and 7, the major cause of the notification is high CHWR temperature. We believe this kind of diagnostic interpretation can be automated and reliably point to the probable cause of the CHW control problem.

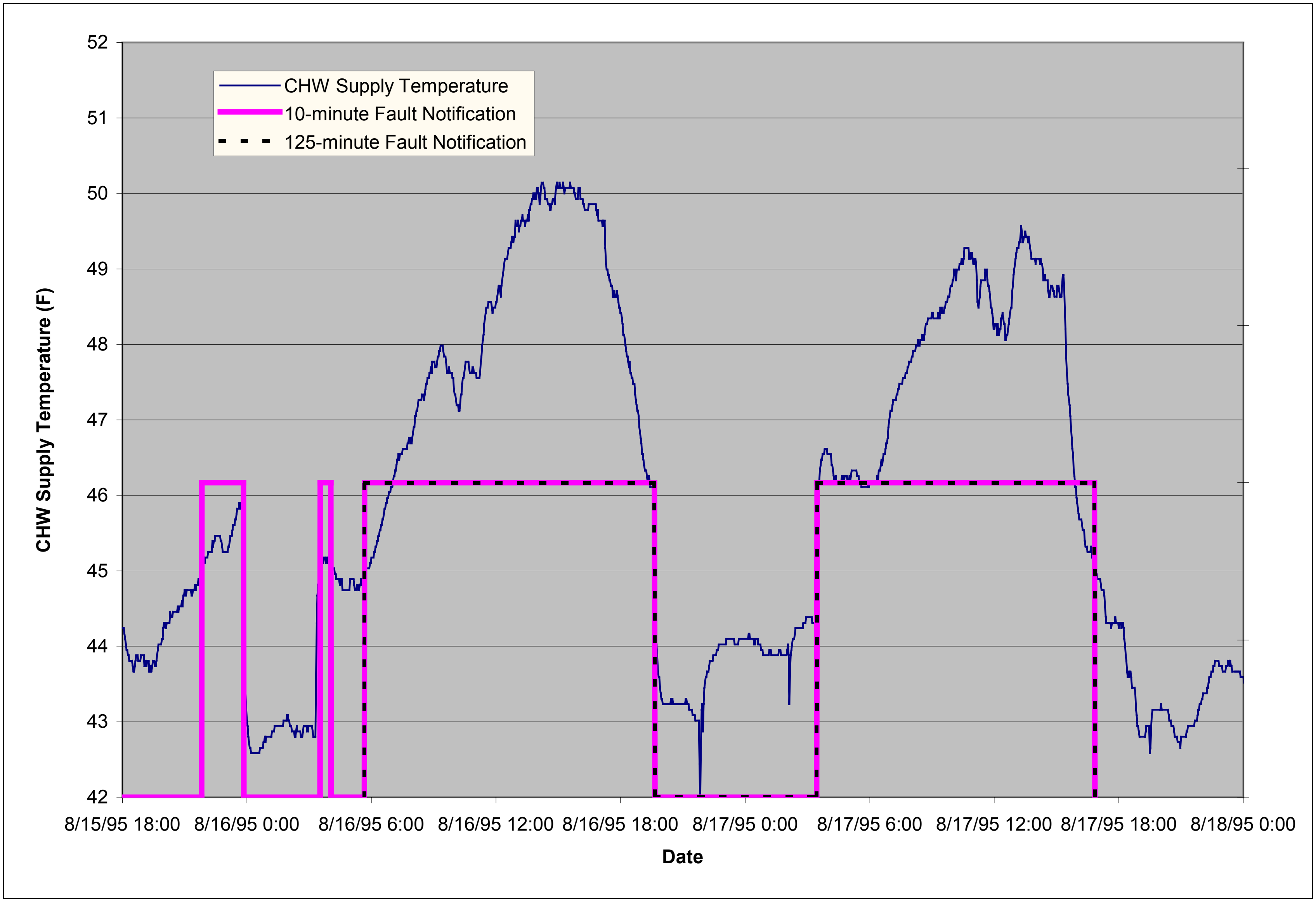

Figure 5. CHWS Temperature and Notification Periods

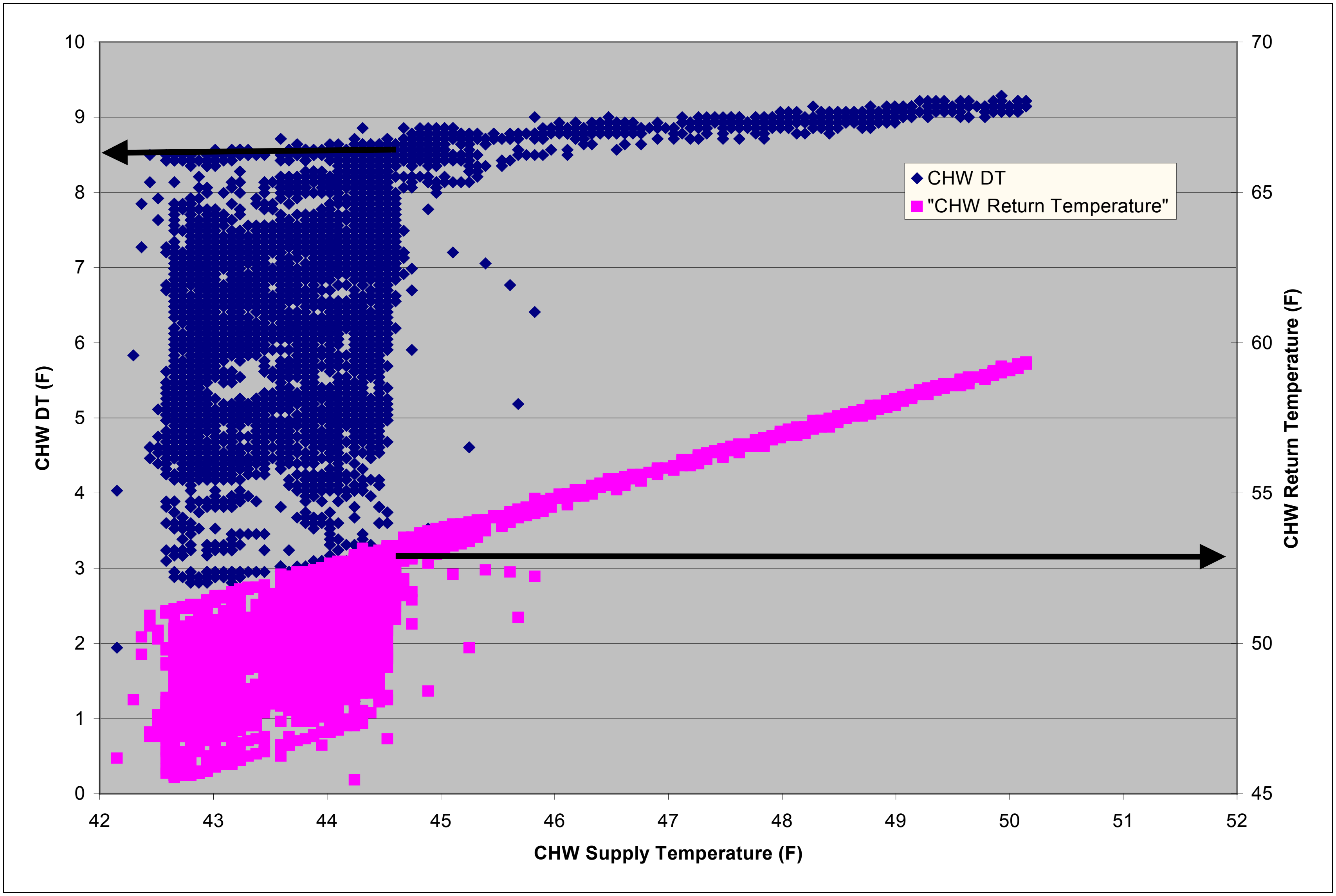

Figure 6. Chiller Operational Criteria versus CHWS Temperature

5 Conclusions

This prototyping and testing exercise produced results that are generally encouraging with respect to the use of the proposed rule-based approach to automating fault detection and diagnostics. The Excel VBA prototype enabled us to take the procedures that we had captured from AEC's experience with ENFORMA, implement them in a software environment using rules, and run them on some real-world data, producing valid results. While the prototype implementation emulates a diagnostic that runs on a periodic basis, this experience lends good support for use of these same methods in a continuous monitoring mode of operation.

A copy of the software is attached for demonstration viewing by the user. Instructions are included in Appendix A.

An issue that has emerged clearly from the prototyping and testing is the importance of certain setup parameters, in particular those that determine how sensitive the procedure is in reporting mild and short-duration aberrations in chilled water control. There are several different ways that this issue could be addressed, and work planned under the remaining project tasks will address how best to handle this issue. We plan to look at several options. [2]

While not the focus of this report, prototyping and testing of similar diagnostics for boilers were performed as part of this task. Boiler diagnostics present similar problems to chiller CHWS diagnostics, with the exception that hot water supply (HWS) temperature setpoints usually vary as a function of ambient temperature. Boilers represent a less substantial problem than chillers because there are fewer parameters that warrant monitoring and because there are few, if any, interactions. With boilers, the diagnostics focus on hot water supply temperature, hot water return temperature, and pump status. We did not look at such issues as boiler standby losses or boiler efficiency due to the additional measurements that would be required.

The boiler diagnostics that were implemented appear to work well, indicating that the rule-based approach selected is appropriate for implementation of the AEC boiler diagnostics. The same issue of

[2] These options include:

- Automatically tune these setup values using a diagnostic installation procedure. The procedure might run the chiller through a typical start-up sequence and set thresholds automatically based on the observed operating data. This strategy might also work with longer term data, such as from the first few days, weeks, or even the first season the chiller is operational. In addition to generating the startup parameters, the reliability and accuracy of the measurements should be established; commissioning the system will likely result in better performance from the diagnostics.
- Alternatively, recommended tuning parameters could be developed during use of the software in field tests of the final software product.
- An option that may be compatible with either of the above approaches would be to make these tuning parameters customizable by the building operator. A convenient method could be developed to enable an operator to reduce the system sensitivity following an event (or events) determined to represent a false positive fault detection. This sensitivity tuning might be simplified to give the user the ability to change the sensitivity of the diagnostics without the complexity of tuning each parameter individually. This approach has been used successfully by Battelle with the Whole-Building Diagnostician.

determining when to issue a fault notification to the user exists with boilers and should be amenable to the same techniques that are being developed for use with chillers.

6 References

Architectural Energy Corporation (AEC). 2000. *ENFORMA, Demonstration and Installation CD-ROM, HVAC Analyzer v3.116, Lighting Evaluation System v.2.2, MicroDataLogger-DataManager Software v3.0.2.1.* Boulder, Colorado.

Architectural Energy Corporation (AEC). *ENFORMA Portable Diagnostic Solutions HVAC Analyzer User's Guide.* Boulder, Colorado.

Microsoft Corporation. 1985-1997. *Microsoft Excel.* Redmond, Washington.

Microsoft Corporation. 1987-1996. *Microsoft Visual Basic.* Redmond, Washington.

Appendix A: Instructions for Use of the Test Prototype

The following is a brief description of how to use the CHW Diagnostics prototype. Four data sets have been provided as input data. They are listed in the table below.

1. To run an analysis, first select which data set in the table you will run. Suggested values for CHW setpoint and maximum allowable CHW variation are provided in Table 1. Change these values in the "UI Mockup" sheet of the file.
2. Click the button labeled **Run Analysis.** A dialog box will be displayed to allow selection of a data set. Select the desired data set and click **OK**. At this point, the analysis procedure will proceed automatically.
   Hint: Since the dialog doesn't completely disappear when you click **OK**, to view all the fields on the UI Mockup sheet, move the dialog box to another position on the screen before clicking OK.

Chilled Water Setpoint: The desired CHW supply temperature

Max CHW Variation: The maximum allowable CHW supply temperature, positive or negative.

max dCHWT/dt for stable operation: The criteria used to determine when the chiller has reached "steady-state" operation.

Minimum Fault Duration for Alarm: The minimum amount of time that a fault must exist before a notification is issued in the lower right-hand table.

Table 1. Data sets and suggested inputs

		Suggested values for inputs:			
Data set:	**Location, building type**	**Chilled Water Setpoint**	**Max CHW Variation**	**max dCHWT/dt for stable op**	**Minimum Fault Duration for Alarm**
Newport Data	Newport, RI; Newport hospital	43	2	0.2	30
Dade County Ch2	Dade Cty FL; Dade County prison	45	3	0.2	20
MethodistHosp#2	Houston, TX; Hospital	42	1.8	0.2	30
Sample 1	Sample project provided with Enforma® software	41	2	0.2	10

The fault notifications are listed in the fault notification table, which is in the lower right corner of the UI mockup. Table 2 shows the headers in the fault notification table, and Table 3 provides definitions for the headers.

Table 2. Fault Notification Headers

Fault Notifications					CHW DT Cause		High CHWR Cause	
Current Time	Fault	Fault Duration	CHW Avg Dev	CHW Std Dev	Avg CHW DT	% of Cause	Avg CHW RT	% of Cause

Table 3. Description of Fault Notification Headers

Field	**Description**
Current Time	Time that the fault started
Fault	The fault (CHWS too high; CHWS too low)
Fault Duration	The duration of the fault in minutes
CHW Avg Dev	The average deviation of the CHWS temperature from the setpoint
CHW Std Dev	The standard deviation of the difference between CHWS temperature and the setpoint.
CHWDT Cause	Evaluation of whether the CHW Delta Temperature was the cause of CHWS not meeting specification.
Avg CHW DT	The average CHW DT during the notification period
% of Cause	The percent of time during the notification period that the CHW DT was determined to be the cause of CHWS not meeting specification.
CHWR Cause	Evaluation of whether the CHW Return Temperature was the cause of CHWS not meeting specification.
Avg CHW RT	The average CHW Return Temperature during the notification period
% of Cause	The percent of time during the notification period that the CHWRT was determined to be the cause of CHWS not meeting specification.

PNWD-3316

Task Report for the

Energy Efficient and Affordable Small Commercial and Residential Buildings Research Program

a Public Interest Energy Research Program

sponsored by the California Energy Commission

Project 2.5 – Pattern-Recognition Based Fault Detection and Diagnostics

Automated Diagnostics Software Requirements Specification

Version 1.1

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Revision History

Date	Version	Description	Author
7/31/2002	1.0	Initial version	DR Sisk, MR Brambley, TA Carlon, RS Briggs
8/30/2003	1.1	Revised version with Boiler Diagnostics	DR Sisk, MR Brambley, TA Carlon, RS Briggs

Table of Contents

Software Requirements Specification

1. Introduction

This document specifies requirements for a computerized automated diagnostic tool for the detection of faults in certain heating, ventilation, and air-conditioning (HVAC) system components. The automated diagnostic tool is being developed for Architectural Energy Corporation (AEC) by Battelle as part of a program sponsored by the California Energy Commission (CEC). Supplemental cost-share funds are provided by U.S. Department of Energy through the Pacific Northwest National Laboratory (PNNL).

1.1 Purpose

This Requirements Specification (RS) specifies the essential capabilities required of the automated diagnostic tool. The purpose of this document is to clarify for AEC, the California Energy Commission (CEC), the Office of Buildings Programs, Office of Energy Efficiency and Renewable Energy (EERN) of the U.S. Department of Energy, and the project team the results that must be achieved by the automated diagnostic tool. Any illustrative model presented in this document is used solely to explain the requirements and is NOT intended to address design or implementation issues.

This SRS also specifies key AEC, CEC, and EERN requirements for project deliverables, including documentation.

1.2 Scope

The automated diagnostic tool detects and identifies faults in chillers and cooling tower subsystems of HVAC units using sensed data acquired from the unit, unit specifications, unit installation and configuration data, and unit operation data (such as schedules). The tool is a software product that will be utilized primarily by building operators and facilities managers and only secondarily by HVAC service technicians, energy service providers, and operation supervisors. Building operators will use the tool to monitor units for which they are responsible, perhaps monitoring from a central control room within the building. Service technicians will utilize the product on site during repair and maintenance visits or off site between visits. Energy service providers, responsible for a number of customers and facilities, will use the product to monitor a number of units remotely, possibly in many different buildings, checking for inefficiencies and problems requiring dispatch of service personnel. Finally, building operator supervisors will use the tool to guide decisions on the assignment of operators and prioritization of work. The tool will provide the user with a visual indication of faults, descriptive information concerning the faults and their causes, and suggested corrective actions. The tool will store the results of diagnostics for subsequent retrieval and use.

The software requirements described in this document are applicable to HVAC systems and associated subsystems. Such subsystems can include chillers, cooling towers, and boilers. However, the initial version of the tool will focus on diagnostics for chillers and cooling towers only. The tool will automate diagnostic processes hitherto performed through a visual analysis of graphical data by a human expert.

The “Product Overview” section describes factors that affect the software and its requirements. The “Concept Example” appendix describes how the software would function in an example situation.

1.3 Definitions, Acronyms and Abbreviations

Some of the following definitions are taken or adapted from IEEE Std 610.12-1990 (IEEE 1993a) and IEEE Std 830-1984 (IEEE 1993b).

Authenticate — the process by which the tool establishes the identity and privileges of the user by obtaining an identifier and password from the user and checking it against a database of predefined users. The user becomes authenticated when the identifier and password match one of the predefined users in the tool's database.

component — one of the parts that make up a software system. A component may be subdivided into other components [IEEE Std 610.12-1990]. Note: For the purpose of this specification, the term "component" will be used in preference to the term "module"

diagnostic result — the output of the diagnostic processing. This can either be an identified fault condition or the confirmation of the absence of a fault condition.

fixed data — data describing the characteristics of the unit under diagnosis, for example, specifications and design information, operating characteristics, set points, installation and configuration data, and operation data (such as schedules) that do not change on a regular basis.

functional requirement — a requirement that specifies a function that a software system or software component must be able to perform [IEEE Std 610.12-1990]. In this requirements specification, functional requirements specify how the inputs to the software product should be transformed into outputs [IEEE Std 830-1984].

interface requirement — a requirement that specifies an external item with which a software system or software component must interact, or that sets forth constraints on formats, timing, or other factors caused by such an interaction [IEEE Std 610.12-1990]

module — see *component*

product — (for this document) a software system or software component–along with any necessary data and documentation–for which requirements are specified in a *requirements specification*

requirement — (1) a condition or capability needed by a customer to solve a problem or achieve an objective; (2) a condition or capability that must be met or possessed by a software *system* or software *component* to satisfy a contract, standard, *specification*, or other formally imposed document; (3) a documented representation of a condition or capability as in (1) or (2) [adapted from IEEE Std 610.12-1990]

requirements specification (RS) — a document of the essential *requirements* (functions, design constraints, and attributes) of the software and/or hardware and their external interfaces [adapted from IEEE Std 610.12-1990]

RS — *requirements specification*

Sensed data — data that are measured through electronic or mechanical detection. Typically this data varies at such a rate, e.g., in real time, hourly, daily, weekly, or is otherwise difficult to estimate or model such that an accurate characterization of it can only be gained through such detection. This data includes temperatures, pressures, electrical current, machine state, etc.

software system — a collection of software *components* related in such a way as to produce a result greater than what their parts, separately, could produce

subsystem — a discrete part of an HVAC system, e.g., chiller or cooling tower.

unit — a complete HVAC system

usability — the ease with which a user can learn to operate, prepare inputs for, and interpret outputs of a software system or software component [IEEE Std 610.12-1990].

1.4 References

The following are references supporting these specifications:

1.5 Overview

Product Overview -- This section provides a descriptive overview of the automated diagnostic tool, its users and operating environment, and general factors that affect requirements. It lays the foundation for understanding the specific requirements that follow.

Specific requirements are specified in the following categories:

Category	Descriptions
Overall Description	An overview of the expected product use and context including user characteristics, constraints, and assumptions.
Functional Requirements	describes the core capability and operating characteristics required of the diagnostic tool by the client.
External Interface Requirements	includes general user interface requirements and logical characteristics of interfaces between the automated diagnostic tool, data acquisition system, and data storage system. Specific user interface requirements are being developed independently as part of the Phase A Prototype.
Security Requirements	specifies requirements for safeguarding customer data
Other Requirements	includes special operations required by end users, and documentation requirements specified by the client.

Appendix A: Data Flow Diagrams of Diagnostic Processes for Chillers, Cooling Towers and Chilled Water Distribution provides diagrams showing the data flows and data-processing that lead from fixed data and sensed data to diagnostic conclusions.

Appendix B: Data Dictionary for Chillers, Cooling Towers and Chilled Water Distribution provides a tabular listing of known system data corresponding to their use in Appendix A.

Appendix C: Data Flow Diagrams for Basic Boiler Diagnostics provides diagrams and mini-specs showing data flows and data processing that lead from fixed data and sensed data to diagnostic conclusions.

Appendix D; Data Dictionary for Boilers provides a tabular listing of all known system data elements corresponding to their use in Appendix C.

2. Overall Description

The following overview of the automated diagnostic tool supplies context for the specific requirements presented in later sections. The purpose of this information is to make the specific requirements easier to understand. All specific requirements are *numbered* in later sections.

2.1 Product Perspective

Currently, diagnostics on HVAC units and subsystems are performed largely on a manual basis. Sensed data, e.g., temperatures and pressures, are obtained from one or more data acquisition devices. These devices measure and store sensed data over periods of several days to several weeks. Prior to the diagnostic process, data from these devices is input to graphical display software for visual inspection by a human expert. The expert, relying on technical expertise and results of previous diagnostic experience, evaluates the condition of the unit and subsystems based on visual plots of the data. This process is depicted in Figure 1.

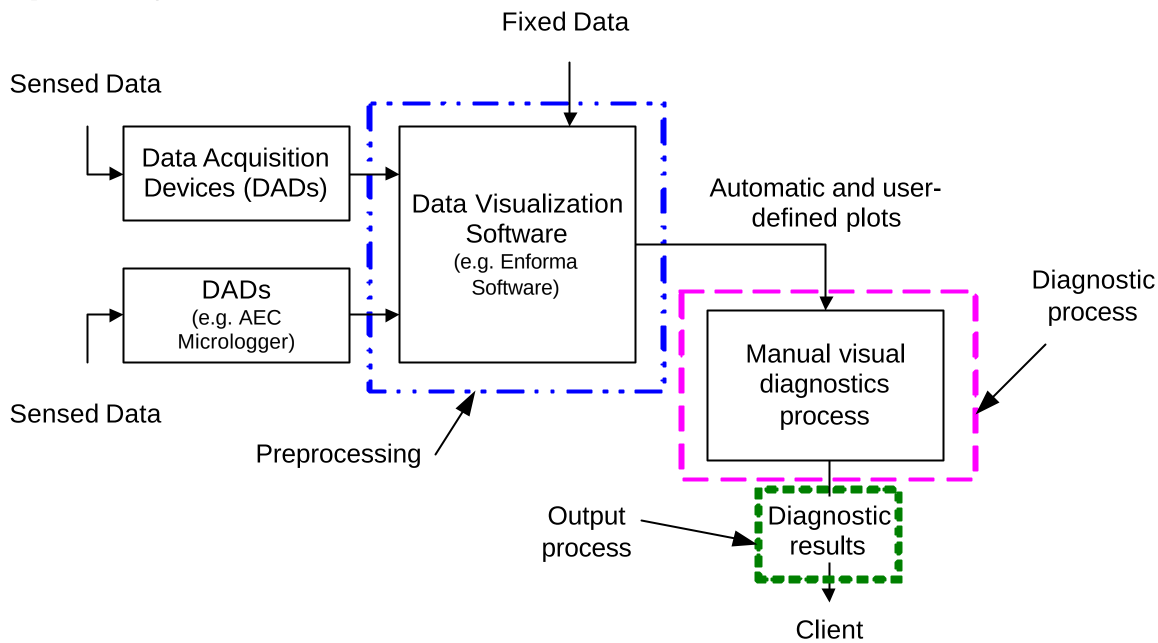


Figure 1. Current HVAC Diagnostic Process

The process depicted in Figure 1 can be partitioned into three logical components. These components are delineated in the diagram by dashed lines and are the data-preprocessing component, the diagnostic component, and output component. The diagnostic tool described in this document will replace the current process with an automated one based on algorithms derived from expert practices. These algorithms operate without the need for data visualization or human expert input. Diagnostic results will be displayed to the user and stored for subsequent retrieval and analysis. For the purposes of this document, the automated diagnostic tool will be assumed to preserve the logical construction of the current process. This construction is depicted in Figure 2.

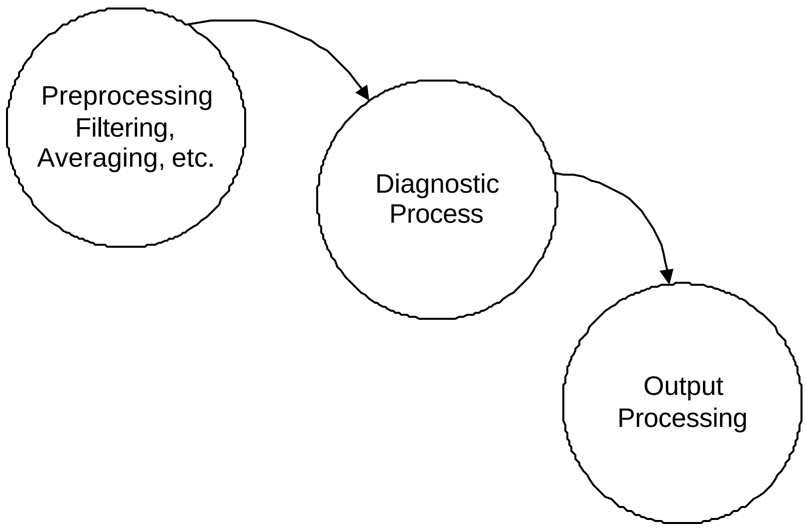


Figure 2. Logical Construction of HVAC Diagnostic Process

2.2 Product Functions

As previously stated, the functionality of the automated diagnostic tool can be partitioned into three logical components: the data preprocessing component, the diagnostic component, and the output component.

The data-preprocessing component obtains data describing the subsystem under diagnosis and reduces, filters, and otherwise prepares the data for input to the diagnostic component. This data includes sensed data, e.g., temperatures, pressures, electrical current, machine state, etc., as well as fixed data describing the characteristics of the subsystem under diagnosis, for example, specifications and design information, operating characteristics and set points, etc. The data may be processed through averaging, trending, or other statistical analysis. Sensed data can originate from data acquisition hardware either in real time or at some arbitrary time after acquisition. Fixed data will generally be compiled prior to operation of the diagnostic tool and be obtained from permanent storage when needed. Specific requirements will be placed on the data-preprocessing component only with respect to types of data to be input and the format and interface requirements of this input. However, the component is described here to provide insight into the operation of the software.

The diagnostic component will detect and identify faults in the operation of HVAC subsystems based on sensed and fixed data input from the data-preprocessing component. The diagnostic algorithms used for fault detection will be derived from current expert practices by AEC. The faults identified by the diagnostic will be enumerated and described under the functional requirements section.

The output component will display and record results output from the diagnostic component. The results of the diagnostics will be displayed to the user in a simple, graphical and textual format. The results will also be stored to permanent storage for subsequent retrieval and analysis.

2.3 User and Environment Characteristics

As previously stated, users of the automated diagnostic tool will include service technicians, energy service providers, building operators, and building operator supervisors. Installed platforms could include portable computers, handheld devices, and personal workstations in control rooms and offices. Installed platforms may communicate with the HVAC unit under diagnosis using wireless interfaces, direct point-to-point connections, or over Internet or local area network. Platform operating systems will be initially restricted to Microsoft Windows-compatible systems.

The computer expertise of the user base could vary over a wide range. Some users could be quite sophisticated, others familiar with only the most rudimentary computer-based tasks. However, it is expected that all users will have a good fundamental understanding of HVAC units. Setting up and operating the automated diagnostic tool should require minimal user input.

Service technicians are expected to use the software as often as their service tasks dictate, perhaps several times a day for periods up to about one hour, in close proximity to the HVAC unit and possibly out of doors. They may also set up the diagnostic tool to collect data continuously offsite at their offices and inspect the data periodically to identify faults or confirm proper operation. Building operators are expected to use the software on an occasional basis every day. The tool would collect data and process it continuously but the operators would only check the results periodically. They may view results for only a few seconds to check the status of equipment while passing through a control room or may sit at a monitor for several minutes more carefully inspecting the diagnostic results and other information available on the tool’s display. Energy service providers and building operator supervisors could potentially use the software in a more continuous mode, allowing it to operate undisturbed for many hours or days to record diagnostic results over a period of time.

See the “Concept Example” appendix for a detailed example of how the automated diagnostic tool will be used.

2.4 General Constraints

The automated diagnostic tool must support a wide variety of users with respect to computer expertise. In addition, different users will have different expectations for the tool with respect to data presentation and functionality. For instance, some users will simply require an immediate diagnostic result while other users may be interested in diagnostic results generated over an arbitrary time that can be subsequently reviewed.

The tool must provide a capability to manually input and edit “fixed” data, i.e., data that does not vary in real-time. Such data includes HVAC unit set points, specifications, and configuration information. This data must be stored for subsequent use by the diagnostic tool for review and verification by other users and management. The tool should provide for configuration management of fixed data.

The user must have the capability to configure the tool for continuous diagnostic analysis over an indefinite period of time. In this mode, the tool will record diagnostic results for subsequent review. No printed reports will be required of the tool, but the tool must print screen images of diagnostic results and historical data at user request and must provide long term storage of diagnostic results and permit the user to supply metadata relevant to the results, e.g., location, HVAC serial number, model number, user name, date, etc.

The tool will not provide capability for additional user-defined analysis of the diagnostic results, results will be provided in a simple, final, definitive manner. However, the tool may provide the user the capability to adjust the sensitivity of the diagnostic algorithms to increase the probability of exposing typically undetected diagnostic events or concealing detected diagnostic events (including false detections).

The tool will be capable of obtaining sensed data from a variety of sources. Such sources should include real-time data acquisition devices and data files containing previously acquired data.

The current version of the tool will include diagnostic algorithms for cooling tower and chiller subsystems of HVAC units. However, the design of the software should support the incorporation of diagnostic algorithms for additional HVAC subsystems. In addition, the tool should support modification or replacement of existing diagnostic algorithms.

The automated diagnostic tool will be restricted to Microsoft Windows-compatible operating systems.

2.5 Use-Case Model Survey

This section provides an overview of the use case model that describes the operation of the user interface. Actual use cases that specifically define the operation of the user interface are presented in the requirements section.

2.5.1 Introduction

The use case model consists of five use cases as depicted in Figure 3. The main actor in the use case model is the human user. This actor is generalized as “User”. The User can be further specified as a general user or administrator. The general user has no ability to modify system settings. The administrator user is able to modify certain settings. The use case “Start and Stop Diagnostics” describes the process by which the administrator user activates and ceases diagnostic processing. The use case “Browse Current Diagnostics” describes the process by which the user views current diagnostic results. The use case “Browse Historical Diagnostics” describes the process by which the user views historical diagnostic results. The use case “Configure Diagnostics” describes the process by which the administrator user adjusts diagnostic parameters used in the diagnostic process. The use case “Authenticate User” describes the process by which the user makes known to the tool the privileges to which they are entitled.

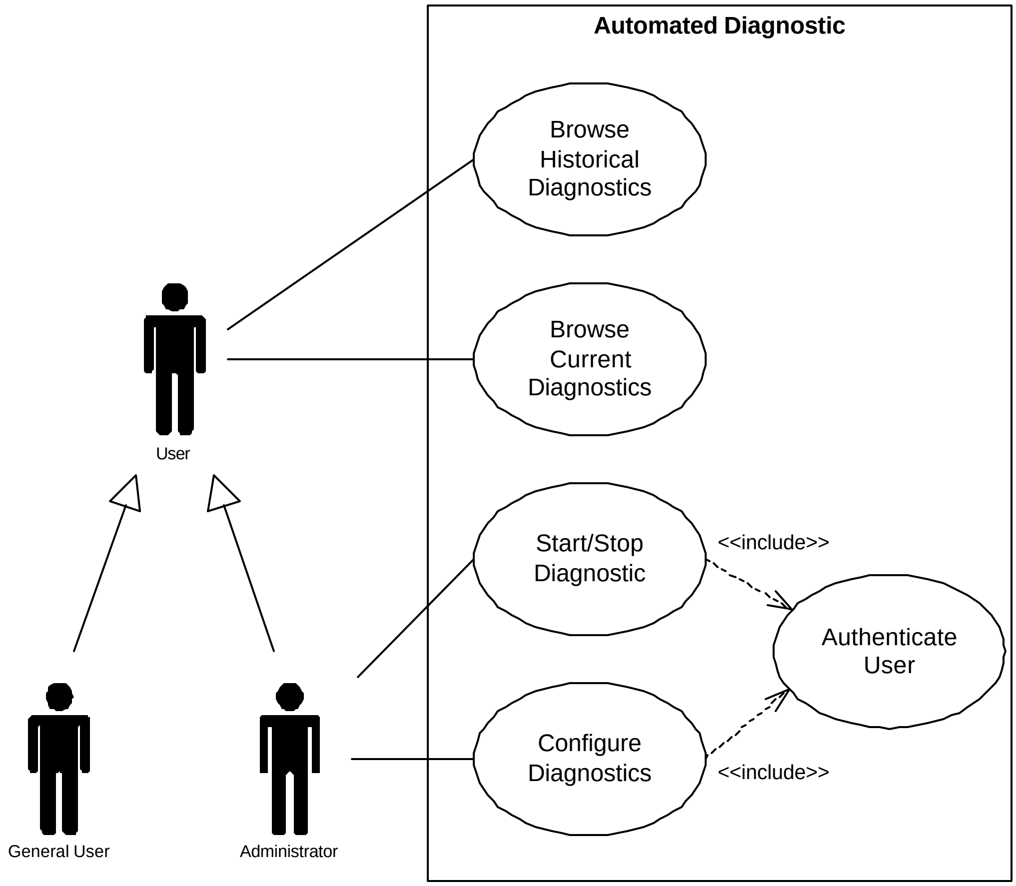


Figure 3. Use Case Model

3. Requirements

The requirements in this document are organized according to the categories listed in Table 1.

Table 1. Categories of Software Requirements

Requirement Category	General Description and Purpose
Use-Case Specifications	specify, in terms of use cases, the expected interactions and behavior of the software with respect to the defined actors.
Functionality	specify functions that a system or component must be able to perform — the fundamental software actions that transform inputs into outputs

Usability	specify factors affecting how easily users can learn to operate a system or component, prepare its inputs, and interpret its outputs
Supportability	include requirements affecting how easily a system or component can be maintained to meet its original requirements or extended to meet modified requirements
Interfaces	specify requirements for user, hardware, software, and communication interfaces, as applicable.
Security	specify needs for protecting the software from accidental or malicious access, use, modification, destruction, or disclosure
Other Requirements	include special requirements that do not fit into previous categories

3.1 Use-Case Specifications

This section describes the five main use cases describing the functionality of the user interface. These use cases are “Start and Stop Diagnostics”, “Browse Current Diagnostics”, “Browse Historical Diagnostics”, “Configure Diagnostics”, and “Authenticate User”. The use cases “Start and Stop Diagnostics” and “Configure Diagnostics” include the use case “Authenticate User”.

3.1.1 Start and Stop Diagnostics Use Case

3.1.1.1 Brief Description

This use case provides the actor the means to start and stop diagnostic processing. The actor in this case is the administrator user (see 2.5.1).

3.1.1.2 Flow of Events

The use case begins just prior to when the user launches the application.

3.1.1.2.1 Basic Flow – Start Diagnostics

1. The user launches the tool by double-clicking the icon associated with the tool or typing the application’s name.
2. The tool momentarily displays a splash screen identifying the tool, identifying developing and sponsoring organizations as appropriate, and listing copyright information.
3. The tool displays the main window of the tool.
4. The user starts the diagnostic processing by selecting a menu item named “Start Diagnostics” from a drop down menu named “Status”.
5. Include (Authenticate User). If the user has the appropriate privilege (i.e., the user is the administrator user) the tool requests a confirmatory response from the user to start the diagnostic processing.
6. If the user confirms the desire to start diagnostic processing, the tool starts the processing and displays

an animated indication that diagnostic processing is active.

7. If the user responds negatively to the confirmation, the tool does not start the diagnostic processing but the user remains authenticated.
8. If the user does not have the appropriate privilege, the tool does not start the diagnostic processing.
9. The user secures the tool by selecting a menu item named “Logout” from the drop down menu named “File”.
10. The tool returns the current user’s privileges to those of the general user.
11. If a period of 15 minutes elapses whereby the user does not secure the tool, the users privileges will automatically revert to those of a general user.

3.1.1.2.2 Alternative Flow

3.1.1.2.2.1 Stopping Diagnostic Processing

1. The user can stop diagnostic processing at any time after the diagnostic processing has started by selecting the “Stop Diagnostics” menu item from the main menu entitled “Status”.
2. If the user is not authenticated as the administrator user, include (Authenticate User) to validate privileges for stopping diagnostic processing.
3. If the user has the appropriate privilege, the tool requests confirmation to stop diagnostic processing.
4. If the user responds positively to the confirmation, the tool stops diagnostic processing and indicates the stopped condition. Otherwise the software performs no function but the user remains authenticated.
5. If the user selects the “Exit” menu item from the main menu entitled “File” and the diagnostic processing is not active, the tool exits.
6. If the user selects “Exit” and the diagnostic processing is active, include (Authenticate User), if the user is not already validated, to verify the user’s privilege to stop diagnostic processing.
7. If the user is permitted to stop diagnostic processing, the tool stops the processing and exits. Otherwise, the software performs no function.

3.1.1.3 Special Requirements

There are no special requirements for this use case.

3.1.1.4 Preconditions

There are no preconditions for this use case.

3.1.1.5 Postconditions

There are no postconditions for this use case.

3.1.1.6 Extension Points

There are no extension points for this use case.

3.1.2 Browse Current Diagnostics Use Case

3.1.2.1 Brief Description

This use case provides the actor the means to view current diagnostic results. The actor in this case is the user (see 2.5.1).

3.1.2.2 Flow of Events

The use case begins with the tool executing and displaying a list of buildings under diagnosis on the main (initial) window.

3.1.2.2.1 Basic Flow – Browse Current Diagnostics

1. The tool displays the main (initial) window, listing buildings under diagnosis.
2. The user selects a building of interest.
3. The tool displays the subsystems window, tiled on top the main (initial) window.
4. The user selects a subsystem of interest.
5. The tool displays the condition window, tiled on top the subsystems window.
6. The user selects a diagnostic of interest.
7. The tool displays the diagnostic information window for that diagnostic.

3.1.2.2.2 Alternative Flow

1. At any window except the initial window, the user may click the "Back" button to dismiss the current window and re-establish the previous window as the current window. The user may then make a new selection.
2. The user may click a button labeled "Print" on the diagnostic information window to print an image of the window.
3. The tool displays a window listing possible items to print including the diagnostic information window.
4. The user selects the diagnostic information window and clicks the "OK" button to print the window.

3.1.2.3 Special Requirements

There are no special requirements for this use case.

3.1.2.4 Preconditions

There are no preconditions for this use case.

3.1.2.5 Postconditions

The diagnostic processing will not cease or be negatively impacted during the activities of this use case.

3.1.2.6 Extension Points

There are no extension points for this use case.

3.1.3 Browse Historical Diagnostics Use Case

3.1.3.1 Brief Description

This use case provides the actor the means to view historical diagnostic results. The actor in this case is the user (see 2.5.1).

3.1.3.2 Flow of Events

The use case begins with the tool displaying the diagnostic information window, itself displaying a description of a diagnostic of interest.

3.1.3.2.3 Basic Flow – Browse Historical Diagnostics

1. The user clicks the "History" button.
2. The tool displays the diagnostic history window depicting the historical results of the selected condition of interest over the default viewing period in the form of a color map. The window provides a scroll bar for scrolling through historical results if data are available prior to the default viewing period. The default viewing period extends backward one week prior to the current date. Sliding the scroll bar does not change the viewing period displayed. The default time resolution for the window is one hour.
3. The user slides the scroll bar backward or forward to view previous results up to the current time.
4. The tool displays the results within a viewing period of one week, adding results to the beginning or ending of the period while dropping results of the opposite end. The tool does not change the viewing period.
5. The user may close the diagnostic history window by clicking the "Close" button.
6. The tool dismisses the diagnostic history window and the diagnostic information window and makes the condition window the current window.

3.1.3.2.4 Alternative Flows

3.1.3.2.4.1 Changing the Viewing Period

1. The user selects a new viewing period from a list of periods provided by the tool.
2. The tool redisplays the historically data over the new viewing period.

3.1.3.2.4.2 Zooming

1. The user selects a period of time within the displayed viewing period over which to expand or contract in time.

2. The tool expands or contracts the selected period. If expanding, the selected period becomes the new viewing period. If contracting, the new viewing period becomes twice as long as the selected period and encloses it.

3.1.3.2.4.3 Displaying Historical Diagnostic Information

1. The user double-clicks a cell in the history window.
2. The tool dismisses the current diagnostic information window if displayed. After a noticeable delay of approximately one second, the tool displays the diagnostic information window associated with the cell selected.

3.1.3.2.4.4 Browsing Arbitrary History Intervals

1. The user specifies a start time and end time for an historical interval of interest using calendar controls.
2. The tool displays historical results beginning with the first result on or after the specified start time up to the end time. The view is confined to the previously selected viewing period.

3.1.3.2.4.5 General Alternative Flows

1. At the diagnostic information window, the user may click the "Close" button to dismiss the window and make the condition window the current window if the diagnostic history window is not displayed.
2. If the user attempts to close the diagnostic information window and the diagnostic history window is still displayed, the diagnostic information window is dismissed but the diagnostic history window remains.
3. If the condition window is closed, then both the diagnostic information and diagnostic history windows are closed if open.
4. If the user does not specify an end time for the history interval in 3.1.3.2.4.1 Browsing Arbitrary History Intervals (1), it defaults to the current time.

3.1.3.3 Special Requirements

There are no special requirements for this use case.

3.1.3.4 Preconditions

The diagnostic processing need not be active for this use case. A diagnostic information window must be displayed for this use case to begin.

3.1.3.5 Postconditions

The diagnostic processing will not cease or be negatively impacted during the activities of this use case.

3.1.3.6 Extension Points

There are no extension points for this use case.

3.1.4 Configure Diagnostics Use Case

3.1.4.1 Brief Description

This use case provides the actor the means to configure the diagnostic tool. This includes defining the buildings containing systems to be diagnosed, defining the systems themselves, specifying equipment setpoints, selecting diagnostic sensitivity, and modifying fixed data. The actor in this case is the administrator user (see 2.5.1).

3.1.4.2 Flow of Events

The diagnostic tool is executing prior to the processing of this use case and only the main window of the tool is displayed.

3.1.4.2.5 Basic Flow – Configure Diagnostics

1. When presented with the main window, the user may select the “Configure Diagnostics” menu item from the menu entitled “File”.
2. If the user has not already been authenticated as the administrator user, include (Authenticate User).
3. If the user has the appropriate privilege, the tool displays the configuration window.
4. The user may click the “Recall” button to read previously saved changes from a disk file or database.
5. The tool populates the window with the data from the disk file.
6. The user makes the desired changes to the configuration and can click the button labeled “Save” to save the changes. Otherwise, the user can click the button labeled “Close”.
7. If the user clicks the button labeled “Save”, the tool will request confirmation to save the changes.
8. If the user confirms, the tool will request a name for the disk file in which to save the modified data to permanent storage.
9. The user will enter a name for the file or cancel the operation.
10. If the user enters a name for the file, the tool will save the changes. If the user cancels the operation, the tool will perform no function.
11. If the tool completes the save operation, the tool will ask the user if the changes are to be relayed to the diagnostic processing for immediate use.
12. If the user confirms the changes are to be relayed to the diagnostic processing, the tool relays the changes if the processing is currently active. Otherwise, the tool does not relay the changes.
13. If the user clicks the button labeled “Close”, the tool will request confirmation for the close and the potential loss of any changes.

14. If the user confirms, the tool will dismiss the configuration window, ignoring any changes and returns the user to the main window. If the user rejects the initial desire to close, the tool will perform no function.

3.1.4.2.6 Alternative Flows

There are no alternative flows for this use case.

3.1.4.3 Special Requirements

There are not special requirements for this use case.

3.1.4.4 Preconditions

The main window of the tool must be the only window active for the tool prior to execution of this use case.

3.1.4.5 Postconditions

Any changes made by the administrator user to the diagnostic tool will take affect immediately if requested by the user.

3.1.4.6 Extension Points

There are no extension points for this use case.

3.1.5 Authenticate User

3.1.5.1 Brief Description

This use case establishes the privileges of the user for certain functions of the tool.

3.1.5.2 Flow of Events

This use case begins when another use case requires its instantiation.

3.1.5.2.7 Basic Flow

1. The tool displays a window for entry of authenticating information, i.e., user name and password, to validate and establish the privileges of the user.
2. The user enters their user name and password.
3. The tool attempts to authenticate the user and indicates whether authentication has succeeded or not.
4. If authentication is unsuccessful, the user is returned to the authentication window to reenter the information.
5. The tool permits three attempts at authentication before dismissing the authentication window and returning the user to the previous window.
6. The user may cancel the authentication process at any time and return to the previous window.

3.1.5.2.8 Alternative Flows

There are no alternative flows for this use case.

3.1.5.2.9 Special Requirements

There are no special requirements for this use case.

3.1.5.2.10 Preconditions

There are no preconditions for this use case.

3.1.5.2.11 Postconditions

There are no postconditions for this use case.

3.1.5.2.12 Extension Points

There are no extension points for this use case.

3.2 Functionality

This section describes the functional requirements of the software, that is, requirements describing the core functions the software must perform. This section begins with general requirements relevant to the tool as a whole. Subsequently, requirements are organized by the logical construction of the tool as data processing progresses from preprocessing to output processing.

3.2.1 General

The following general requirements pertain equally to the logical partitions of the tool.

3.2.1.1 Users of the tool shall be classified into two types. The first type, general user, shall only be permitted to utilize a limited set of the capabilities of the tool. These capabilities are listed in Table 2. Typically a general user is only permitted to view the results of diagnostic processing either current or historical. The second type, administrator, shall be permitted all the privileges of the general user plus those identified in Table 2. The administrator is permitted all the privileges of the general user in addition to the privileges to configure the system and modify fixed data and diagnostic settings.

Table 2 User Privileges

General User Privileges	Administrator Privileges Beyond General User's
Browse Current Diagnostics	Start/Stop Diagnostics
Browse Historical Diagnostics	Configure Diagnostics
	Define sensed data input units

3.2.2 Preprocessing

The automated diagnostic tool shall input sensed data in real time from data acquisition devices and the HVAC unit under diagnosis as well as from data files containing previously acquired data, though not simultaneously. In addition, the tool shall input fixed data provided by the user. Sensed and fixed data used by the tool in performing automated diagnostics shall be stored to permanent storage for post-analysis by the diagnostic process and viewing of the results.

3.2.2.1 The tool shall input sensed data in real time from data acquisition devices and the HVAC unit under diagnosis. The absolute time of input will be associated with each sensed data item for its complete lifecycle, including permanent storage. The time will be determined at the instant the acquisition of the sensed data is complete.

3.2.2.2 The tool shall permit sensed data to be input from an electronic file, though not simultaneously with sensed data from external acquisition hardware. When inputting sensed data from an electronic file, only one file shall be used containing all necessary sensed data. The file shall be an ASCII text file containing only columns delimited by a single tab character or single comma. The file shall begin with a required header. The first column of the header will list, at a minimum, the entries ""Building Identifier" and "Input Identifier" in that order. Following columns on the Input Identifier row will list integer input identifiers. Following columns on the Building Identifier row will list corresponding integer building identifiers for the inputs. One or more comment rows may exist above and below these required rows. These comment rows are identified by a '#' as the first character of the first column. These rows are ignored by the tool. The first uncommented column in the file after the required headers shall list the absolute time, in ascending order, associated with all entries in subsequent columns of the row. Each additional column in the file shall pertain to one and only one sensed parameter. Data values in the same row of the file correspond to identical time values. All columns in the file shall have the same number of rows. An example input file is presented in Table 3. When the tool is processing sensed data from an input file, the tool is considered to be operating in "batch mode".

Table 3 Example Input Data File Reflecting Specified Format

#Test Run			
#Sensor Name	Temperature	Flow	Pressure
Building Identifier	1	1	2
Input Identifier	1	2	3
12/14/01 8:43	12.4	35.8	407.3
12/14/01 13:30	5.4	955.1	971.0
12/14/01 20:01	123.5	576.21	491.4

3.2.2.3 Each sensed data item will be qualified as to its certitude during the acquisition process. Sensed data will be considered in doubt if acquisition of the data was not possible (for example, if an error occurs during communication with the acquisition hardware), or the data is outside the range of possible values. Otherwise, the sensor value will be deemed accurately acquired.

3.2.2.4 The software will deem sensed data in doubt if acquisition of the data is not possible, due to communication failures, for a default number of successive samples. The default is dependent on sensor type. These default values are specified in Table 4. The number of successive samples for a given sensor type shall be modifiable by the administrator. Data not successfully acquired will be deemed "missing data".

Table 4 Default Number of Failed Successive Samples Indicating Sensor Data Acquisition Problem.

Sensor Type	Default Number of Failed Successive Samples
Temperature	3
Current	3
Switch	3

3.2.2.5 Sensed data used in or supporting diagnostic analyses shall be saved to permanent storage.

3.2.2.6 The occurrence of missing data shall be indicated in permanent storage by a unique and obvious place holder or indicator, e.g., a null value or sequence of characters that cannot be confused with non-missing data.

3.2.2.7 Sensed data input to the tool shall be stored to permanent storage with a precision of three significant figures.

3.2.2.8 Sensed data input to the tool shall be validated with respect to its expected range of values. Sensed data shall be assigned the ranges listed in Table 5 by default.

Table 5 Default sensed data expected ranges

Sensor	Expected Minimum Value	Expected Maximum Value
Ambient Temperature	-40 F	130 F
Ambient wet-bulb Temperature	-40 F	100F
Chilled Water Supply Temperature	30F	80F
CT Sump Temperature	32F	130F
CT Inlet Temperature	35F	130F
Compressor Current (or Power)	0	NA, Chiller dependent
Condenser Pump Current (or Power)	0	200 amps
Chilled Water Pump Current (or Power)	0	200 amps
Secondary Chilled Water Pump(s) Current (or Power)	0	200 amps
Cooling Tower Fan(s) Current (or Power)	0	200 amps
Condenser Fan(s) Current (or Power)	0	200 amps
Supply Fan(s) Current (or Power)	0	1000 amps

3.2.2.9 The administrator shall have the capability to modify the expected range of sensed data against which the data will be validated.

The engineering units of sensed data input to the tool shall comply with the units listed in

3.2.2.10 Table 6 for the associated physical parameter measured prior to input to the diagnostics.

The tool shall provide the capability to convert sensed data not provided in the units listed in

Table 6 to the required units.

Table 6. Required engineering units for sensed data.

Physical Parameter	Engineering Units for Sensed Data
Temperature	Degrees F
Current	Amps

3.2.2.11 The tool shall associate with each continuous parameter one or more tolerances each corresponding to a different sensitivity level for the tool.

3.2.2.12 Any and all errors associated with obtaining, validating, converting, or storing the sensed data shall be logged as described in subsequent specifications and selected errors shall be reported to the user.

3.2.3 Diagnostic Process

The automated diagnostic tool shall detect and identify certain performance and operational faults in chiller and cooling tower subsystems of HVAC units following specified algorithms. In addition, the tool shall be designed to permit expansion of diagnostic analysis to additional subsystems. The faults identified and their causes and sources, shall be saved to permanent storage for subsequent analysis.

3.2.3.1 The tool shall monitor performance and operational parameters listed in Table 7 for chillers and cooling towers and identify the specific faults in the specific fault categories listed in the table.

Table 7. Performance and Operational Parameters Monitored by the Automated Diagnostic Tool and Specific Faults Identified

Subsystem(s)	Monitored Parameter	Fault Category	Fault
Chiller	Chilled Water Supply Temperature Maintenance	Chilled Water Supply Temperature not Maintained Correctly	The chilled water supply temperature is too high
			The chilled water supply temperature is too low
	Chiller Schedule	Chiller Schedule is Incorrect/in Error/Corrupt/Inefficient/not Followed	The chiller is on when it should be off. Energy is being wasted.

	Compressor Cycling	Compressor Cycling is Abnormal	The compressor is cycling on too frequently. It is not staying off for the minimum required off time.
			The compressor is cycling off too frequently. It is not staying on for the minimum required on time.
	Compressor and Condenser Fan Interlock (for air-cooled condensers only)	Compressor is Improperly Interlocked with Condenser Fan	The compressor is on while the condenser fan is off. The chiller cannot reject heat and this could damage the compressor
			The condenser fan is on while the compressor is off. The fan is running unnecessarily and wasting energy.
	Compressor and Condenser Pump Interlock (for water-cooled condensers only)	Compressor is Improperly Interlocked with Condenser Pump	The compressor is on while the condenser pump is off. The chiller cannot reject heat and this could damage the compressor.
			The condenser pump is cycling unnecessarily frequently. Repeated frequent cycling will shorten the life of the condenser pump.
			The condenser pump is turning on too much in advance of the compressor and wasting energy.
Cooling Tower	Cooling Tower Fan Cycling	Cooling Tower Fan Cycling Problem	The cooling tower fan is not staying off long enough during cycling.
			The cooling tower fan is not staying on long enough during cycling.
	Sump Temperature Control	Sump Temperature is Improperly Controlled	The cooling tower fan is off but should be on. As a result, the condenser water is not being cooled sufficiently.
			The cooling tower fan is on but it should be off. Energy is being wasted.
	Cooling Tower Approach	Cooling Tower Approach Problem	The cooling tower approach is greater than the Approach Benchmark provided in set up. Heat rejection from the cooling tower is less than expected.

	Cooling Tower Fan Staging	Cooling Tower Fan Staging Problem	The Sump temperature is above the cooling tower fan “on” set point, but all cooling tower fans are not on. This indicates a problem with the fan staging and, as a result, the cooling tower is not maintaining the sump temperature as low as it should.
			A fan is on even though the sump temperature is below the “off” set p oint. This indicates a fan staging problem, and energy is being wasted. All cooling tower fans should be off.
	Cooling Tower Range	Cooling Tower Range Problem	The cooling tower range is below its benchmark. As result, heat rejection by the cooling tower is less than expected and the cooling tower is performing at less than its capacity.
Chilled Water Loop	Supply Fan(s) and the Primary-Loop Chilled Water Pumps Interlock	Supply Fan(s) and the Primary-Loop Chilled Water Pumps are not Interlocked Properly	The is possibly a problem with the supply fan control.
			This chilled water pump is being operated unnecessarily and is wasting energy. The chilled water pump should not operate unless at least one of the supply fans in an air handling unit served by the chilled water pump is on.
	Supply Fan(s) and the Secondary-Loop Chilled Water Pumps Interlocked	Supply Fan(s) and the Secondary-Loop Chilled Water Pumps are not Interlocked Properly.	Possible problem with secondary chilled water pump control—check to see if loads in the spaces served are being met for all supply fans that are part of air handlers served by this secondary chilled water loop and that is on when the secondary chilled water pump is off.

			The secondary chilled water pump and some of the supply fans that are served by it are not interlocked properly. This secondary chilled water pump is operating unnecessarily when all supply plans it serves are off and, as a result, is wasting energy. The secondary chilled water pump should not operate unless at least one of the supply fans in an air handler served by this pump is on.
	Secondary and Primary Loop Chilled Water Pumps Interlock	Secondary and Primary Loop Chilled Water Pumps are not Interlocked Properly	The secondary chilled water pumps that are on are wasting energy. Secondary chilled water pumps should only operate when the primary CHW pump is operating.
Chiller/Cooling Tower	Cooling Tower Fan(s) and Condenser Pump Interlock	Cooling Tower Fan(s) and Condenser Pump are not Interlocked Properly	The cooling tower fan and condenser pump are not interlocked properly. Energy is being wasted because the cooling tower fan should be off when the condenser pump is not operating.
			The interlock between the condenser pump and the cooling tower may not be properly implemented. The cooling tower fan may be off when the condenser pump is running, but this should not always be the case.
Chiller/Water Loop	Compressor and Primary Chilled Water Pump(s) Interlock	Compressor and Primary Chilled Water Pump(s) are not Interlocked Properly	The primary chilled water pumps are not interlocked properly with the compressor. The condenser pump is cycling on and off unnecessarily. Repeated frequent cycling will shorten the life of the pump.
			The compressor is not properly interlocked with the primary chilled water pumps. The chiller is operating without a load. Energy is being wasted and damage to the compressor may result.

			The compressor is not properly interlocked with the primary chilled water pumps. Water side economizing is not being used, and the primary chilled water pumps are cycling on too much in advance of the compressor and wasting energy.

3.2.3.2 With each fault identified in Table 7, the tool shall associate text describing the possible problem, causes, and a recommended fix. This text for each fault is listed in Table 8.

Table 8 Text to Associate with Each Anomaly Detected

Subsystem(s)	Fault Category	Fault/Possible Problem	Causes	Fix
Chiller	Chilled Water Supply Temperature not Maintained Correctly	The chilled water supply temperature is too high	1) Chilled water supply temperature set point is set too high. 2) Chiller load exceeds capacity.	
		The chilled water supply temperature is too low	1) Chilled water supply temperature set point is lower than necessary.	
	Chiller Schedule is Incorrect/in Error/Corrupt/Inefficient/not Followed	The chiller is on when it should be off. Energy is being wasted.	Incorrectly specified schedule.	
	Compressor Cycling is Abnormal	The compressor is cycling on too frequently. It is not staying off for the minimum required off time.	1) Incorrectly specified minimum off time in the set-up of this diagnostic, 2) Incorrectly specified minimum off time in the control algorithm for the compressor, 3) a failed relay or mis-adjusted relay, for compressors having the minimum off time controlled by a relay.	

		The compressor is cycling off too frequently. It is not staying on for the minimum required on time.	1) Incorrectly specified minimum on time in the set-up of this diagnostic, 2) Incorrectly specified minimum off time in the control algorithm for the compressor, 3) a failed relay or mis-adjusted relay, for compressors having the minimum on time controlled by a relay.	
	Compressor is Improperly Interlocked with Condenser Fan (for air-cooled condensers only)	The compressor is on while the condenser fan is off. The chiller cannot reject heat and this could damage the compressor	The compressor is on while the condenser fan is off. The interlock between the compressor and condenser fan in the control code is not specified correctly or is overridden.	
		The condenser fan is on while the compressor is off. The fan is running unnecessarily and wasting energy.	The condenser fan is running while the compressor is off. This wastes energy. The interlock between the compressor and condenser fan in the control code is not specified correctly or is overridden.	
	Compressor is Improperly Interlocked with Condenser Pump (for water-cooled condensers only)	The compressor is on while the condenser pump is off. The chiller cannot reject heat and this could damage the compressor.	The compressor is on while the condenser pump is off. The interlock between the compressor and condenser pump in the control code is not specified correctly or is overridden.	

		The condenser pump is cycling unnecessarily frequently. Repeated frequent cycling will shorten the life of the condenser pump.	The Condenser Pump is turning on and off tool frequently.	
		The condenser pump is turning on too much in advance of the compressor and wasting energy.	The Condenser Pump Maximum Start-Up time is not specified correctly or is overridden in the control code.	
Cooling Tower	Cooling Tower Fan Cycling Problem	The cooling tower fan is not staying off long enough during cycling.	1) The timer that is intended to eliminate short cycling is not working. 2) The “on” and “off” control set points for the cooling tower fan are too close to one another.	
		The cooling tower fan is not staying on long enough during cycling.	1) The timer that is supposed to eliminate short cycling is not working properly. 2) The "on" and "off" control set points for the fan are too close to one another. 3) The cooling tower capacity is too great for the load, so the fans rapidly cycle off (i.e., the on time is very short) because the load is met quickly.	
	Sump Temperature is Improperly Controlled	The cooling tower fan is off but should be on. As a result, the condenser water is not being cooled sufficiently.	1) a cooling tower control problem, 2) sump temperature sensor problem, 3) electrical problems such as a motor failure, 4) other problems with the fan motor.	

		The cooling tower fan is on but it should be off. Energy is being wasted.	1) a cooling tower control problem, 2) an actuator or relay has failed.	
	Cooling Tower Approach Problem	The cooling tower approach is greater than the Approach Benchmark provided in set up. Heat rejection from the cooling tower is less than expected.	1) The cooling tower media is fouled due to mineral deposits or ambient dirt, dust, or other contaminants. 2) Restricted airflow for other reasons (e.g., piece of cardboard stuck over part of cooling tower air inlet). 3) There is condenser pump fouling, pipe fouling, or other restrictions on the water side.	
	Cooling Tower Fan Staging Problem	The Sump temperature is above the cooling tower fan "on" set point, but all cooling tower fans are not on. This indicates a problem with the fan staging and, as a result, the cooling tower is not maintaining the sump temperature as low as it should.	1) Different values of the fan "on" set point are specified in the fan controller and this software. 2) Fan staging control algorithm is not correctly specified. 3) A fan motor or electrical connection has failed. 4) The sump temperature sensor has failed or is out of calibration.	
		A fan is on even though the sump temperature is below the "off" set point. This indicates a fan staging problem, and energy is being wasted. All cooling tower fans should be off.	1) Different values of the fan "off" set point are specified in the fan controller and this software. 2) Fan staging control algorithm is not correctly specified. 3) The sump temperature sensor has failed or is out of calibration.	

	Cooling Tower Range Problem	The cooling tower range is below its benchmark. As result, heat rejection by the cooling tower is less than expected and the cooling tower is performing at less than its capacity.	1) Tower media may be fouled due to mineral deposits or ambient dirt, dust, or other contaminants. 2) the airflow is restricted by some other obstruction. 3) The condenser pump is fouling, pipes are fouling, or there are other water-side flow restrictions. 4) The cooling tower is too small for the load (i.e., there is a design problem)	
Chilled Water Loop	Supply Fan(s) and the Primary-Loop Chilled Water Pumps are not Interlocked Properly	The is possibly a problem with the supply fan control.	The chilled water pump is off and the supply fan for at least one air handler served by this pump is on. There may be a problem with the control of this supply fan or other parts of the air handlers with supply fans operating under these conditions.	
		This chilled water pump is being operated unnecessarily and is wasting energy. The chilled water pump should not operate unless at least one of the supply fans in an air handling unit served by the chilled water pump is on.	Improper interlock between the chilled water pump and the supply fans.	

	Supply Fan(s) and the Secondary-Loop Chilled Water Pumps are not Interlocked Properly.	Possible problem with secondary chilled water pump control—check to see if loads in the spaces served are being met for all supply fans that are part of air handlers served by this secondary chilled water loop and that is on when the secondary chilled water pump is off.	Improper interlock between the secondary chilled water pump and the supply fans of air handlers it serves.	
		The secondary chilled water pump and some of the supply fans that are served by it are not interlocked properly. This secondary chilled water pump is operating unnecessarily when all supply plans it serves are off and, as a result, is wasting energy. The secondary chilled water pump should not operate unless at least one of the supply fans in an air handler served by this pump is on.	Improper interlock between the secondary chilled water pump and the supply fans of air handlers it serves.	
	Secondary and Primary Loop Chilled Water Pumps are not Interlocked Properly	The secondary chilled water pumps that are on are wasting energy. Secondary chilled water pumps should only operate when the primary CHW pump is operating.	Improper interlock between the secondary chilled water pump and the supply fans of air handlers it serves.	
Chiller/Cooling Tower	Cooling Tower Fan(s) and Condenser Pump are not Interlocked Properly	The cooling tower fan and condenser pump are not interlocked properly. Energy is being wasted because the cooling tower fan should be off when the condenser pump is not operating.	The cooling tower fan and condenser pump are not interlocked properly.	

		The interlock between the condenser pump and the cooling tower may not be properly implemented. The cooling tower fan may be off when the condenser pump is running, but this should not always be the case.	The cooling tower fan and condenser pump may not be interlocked properly.	
Chiller/Water Loop	Compressor and Primary Chilled Water Pump(s) are not Interlocked Properly	The primary chilled water pumps are not interlocked properly with the compressor. The condenser pump is cycling on and off unnecessarily. Repeated frequent cycling will shorten the life of the pump.	The chilled water pump is cycling between on and off while the compressor is off. The primary chilled water pumps are not interlocked properly with the compressor.	
		The compressor is not properly interlocked with the primary chilled water pumps. The chiller is operating without a load. Energy is being wasted and damage to the compressor may result.	The compressor is running while the primary chilled water pumps are not operating because the compressor is not properly interlocked with the primary chilled water pumps.	
		The compressor is not properly interlocked with the primary chilled water pumps. Water side economizing is not being used, and the primary chilled water pumps are cycling on too much in advance of the compressor and wasting energy.	The primary chilled water pumps are cycling on too much in advance of the compressor turning on.	

3.2.3.3 The tool shall be designed to permit the addition of diagnostic algorithms for other subsystems of HVAC units.

3.2.3.4 A diagnostic algorithm shall not process if any input data to the algorithm is missing. The user shall be notified if a diagnostic algorithm cannot process due to missing data.

3.2.3.5 Any and all errors associated with failures of the diagnostic algorithms shall be logged as described in subsequent specifications and selected errors shall be reported to the user.

3.2.3.6 The tool shall monitor the unit under diagnosis, either in real time or batch mode, for an indefinite period of time or until input data are no longer available, and log diagnostic results as they are determined.

3.2.3.7 Diagnostic results that are saved to permanent storage shall be accompanied in storage by the absolute time of occurrence, the identity of the unit to which the diagnostic applies, and the identity of the diagnostic.

3.2.3.8 The administrator user shall have the capability to adjust the sensitivity of the diagnostic analysis in order to increase or decrease the probability of fault detection.

3.2.4 Output Processing

The automated diagnostic tool shall display and record diagnostic results. Diagnostic results to be displayed to the user will be done so in a simple, graphical and textual format. Diagnostic results shall also be saved to permanent storage for subsequent retrieval, display, and analysis.

3.2.4.1 The administrator shall have the ability to specify which diagnostic results will not be reported in any manner, i.e., not detected.

3.2.4.2 The display of each diagnostic result for fault conditions will include a description of the fault, potential causes of the fault, the location of the fault, and the absolute time of occurrence.

3.3 Usability

This section describes requirements related to the usability of the tool.

3.3.1 User Interface

The following specifies usability requirements for the user interface.

3.3.1.1 The area on the main, systems, and condition windows sensitive to the users selection device, typically the mouse, shall include the line surrounding the item of interest over the entire width of the window. This includes the diagnostic indicators.

3.3.1.2 The windows listing diagnostic results shall increase in height as needed to display entries up to a maximum of ten entries. Once the window has reached maximum size and there are additional items to display, the window shall deploy a scroll bar to permit the user to scroll through the additional entries. In this event, a summary set of diagnostic indicators shall appear above (below) the top (bottom) entry in the display. This set(s) of indicators shall summarize diagnostic indicators not currently appearing on the list above (below) it. An indicator in the summary set shall be active if any similar indicator not appearing above (or below) it is active. The summary set indicators comply with the same specification for activation as other indicators (see 3.5.1.39).

3.3.1.3 The building, subsystems, and condition windows shall display the current time if the diagnostic tool is operating in real time. If the tool is operating in batch mode, the time displayed will be the time associated with the entry currently being processed in the batched input.

3.3.1.4 If only a single building is defined, the subsystems window shall become the main window of the application and shall have all the functionality of the main window as described in these specifications.

3.3.1.5 Each window of the diagnostic tool shall display an animated graphical feature indicating the status, whether active or not, of the diagnostic processing.

3.3.1.6 The subsystem window shall be modal to the building window, the condition window modal to the subsystem window, and the diagnostic history and diagnostic information windows shall be modal to the condition window.

3.4 Supportability

This section describes requirements related to the support of the software after initial installation.

3.4.1 Error Reporting

Significant errors in software operation shall be logged to permanent storage with sufficient detail to guide the administrator and to assist support staff in locating and rectifying the error. In addition, selected errors shall be reported to the user.

3.4.1.1 Software errors logged to permanent storage shall include the absolute time of occurrence, the name of the software module in which the error occurred, the name of the software function in which the error occurred, and a description of the error.

3.5 Interfaces

This section describes requirements related to interfaces of the tool.

3.5.1 User Interfaces

This section describes the specifications for the user interface.

3.5.1.1 The user interface shall consist of six windows: Main window, configuration window, subsystems window, condition window, diagnostic information window, and diagnostic history window.

3.5.1.2 These windows shall be organized in a hierarchy enforcing a navigational order on the user. This hierarchy is depicted in Figure 4. As indicated in the figure, the main window is at the top of the hierarchy and is the first window that appears when the tool begins execution. The configuration window is subordinate to the main window and can only be displayed by a user selection on the main window. The third window in the hierarchy is the subsystems window and it can only be displayed by a user selection on the main window. The fourth window in the hierarchy is the condition window and it can only be displayed by a user selection on the subsystems window. The fifth window is the diagnostic information window. This window can only be displayed by a user selection on the condition window or by a user selection on the diagnostic history window if it is displayed. The diagnostic history window can only be displayed by a user action on the diagnostic information window.

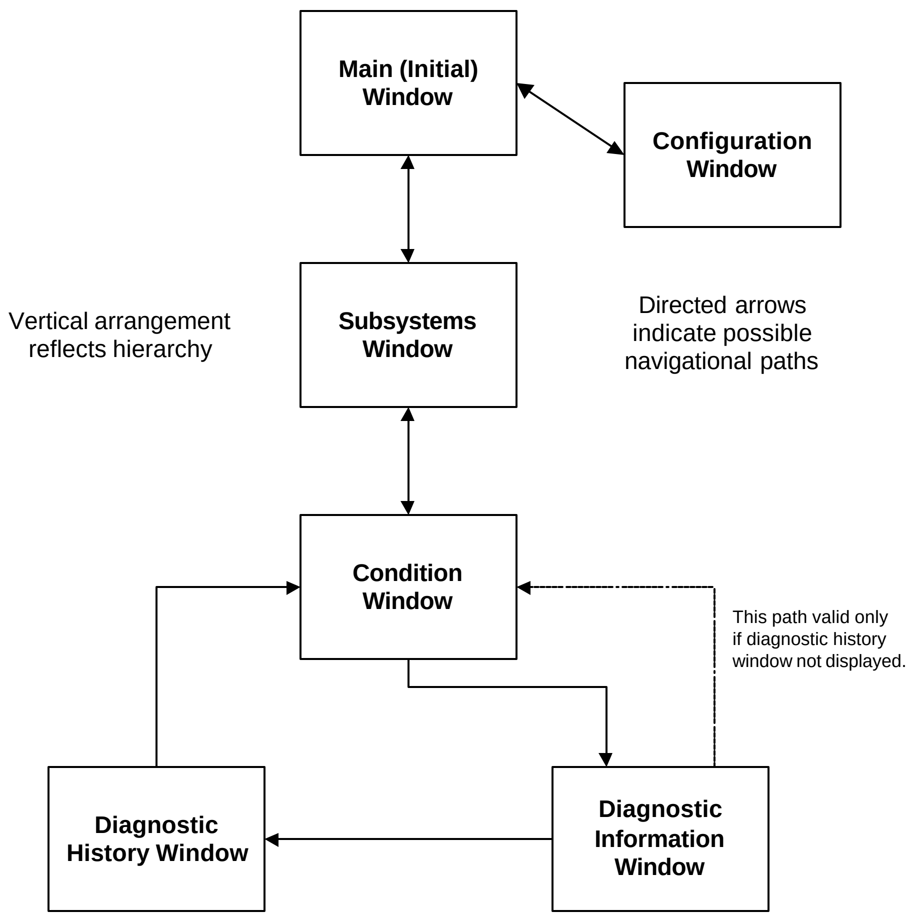


Figure 4 User Interface Window Hierarchy

3.5.1.3 The main (e.g., initial or default) window shall list buildings monitored and summarizing the current diagnostic status of all contained monitored units. A recommended layout for this window is presented in Figure 5. This window shall be titled “Diagnostician”.

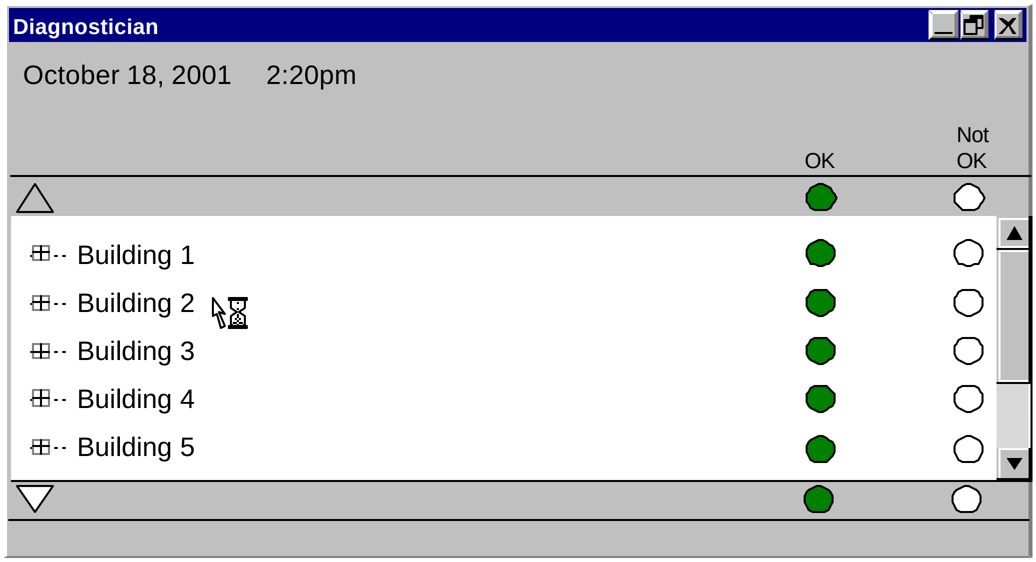


Figure 5 Recommended Layout for Main Window

3.5.1.4 The main window shall have main menus entitled “File” and “Status”.

3.5.1.5 The main menu entitled “File” shall contain the following menu items in the following order: “Configure Diagnostics”, “Logout”, “Exit”.

3.5.1.6 The main menu entitled “Status” shall contain the following menu items in the following order: “Start Diagnostics”, “Stop Diagnostics”.

3.5.1.7 The menu items named “Configure Diagnostics” and “Exit” in the main menu entitled “File” shall be enabled at all times.

3.5.1.8 The menu item named “Logout” in the main menu entitled “File” shall be enabled only if the current user is presently authenticated as the administrator user. Otherwise, this menu item shall be disabled.

3.5.1.9 The menu item named “Start Diagnostics” in the main menu entitled “Status” shall be enabled only if diagnostic processing is not currently running. Otherwise, the menu item shall be disabled.

3.5.1.10 The menu item named “Stop Diagnostics” in the main menu entitled “Status” shall be enabled only if diagnostic processing is currently running. Otherwise, the menu item shall be disabled.

3.5.1.11 Selecting the “Configure Diagnostics” menu item of the main menu entitled “File” shall display the configuration window, making it the current window, modal to the main window.

3.5.1.12 The configuration window shall permit the administrator user to modify the following parameters:

a. The password for the administrator user.
b. A toggle enabling or disabling the main window of the tool as a screen saver.
c. A toggle enabling or disabling the main window’s position on the screen as the top most window.
d. Buildings and subsystems to be monitored and the conditions they will be monitored

for. The conditions will be selected from a list provided by the tool.

e. The enabled state of individual conditions. Disabled conditions will not be processed or displayed.

f. The sensitivity of each condition by selecting a sensitivity from a list provided by the tool.

g. Scale factors for transforming the engineering units of sensed input data to the required units.

h. The expected range of sensed input data.

3.5.1.13 The configuration window shall display the following non-modifiable information:

a.

3.5.1.14 The configuration window shall have a button labeled “Save” that when clicked will present the user with a window by which to enter a disk file or database name in which to save the modifiable data in the window. Entering a file name shall cause the permanent storage of the modified parameters and their immediate use by the diagnostic operations after confirmatory responses by the user. If the user does not confirm the request to save, it will not be performed. If the user does not confirm the request to relay the modified parameters to the diagnostic processing immediately, it will not be performed. In either event, the configuration window will remain displayed.

3.5.1.15 The configuration window shall have a button labeled “Close” that will dismiss the configuration window and return the user to the main window. If the user has made changes to data in the configuration window, the tool will request confirmation of the user’s desire to dismiss the window. If the user does not confirm the request, the window will not be dismissed.

3.5.1.16 The configuration window shall have a button labeled “Recall” that will permit the user to recall a disk file of previously saved parameters from which to populate the configuration window. When functioning as a screen saver, the window shall change location on the screen periodically and will continue to be updated by diagnostic results.

3.5.1.17 The subsystems window shall list subsystems monitored for a specific building and summarizing the current diagnostic status of all monitored subsystems. A recommended layout for this window is presented in Figure 6.

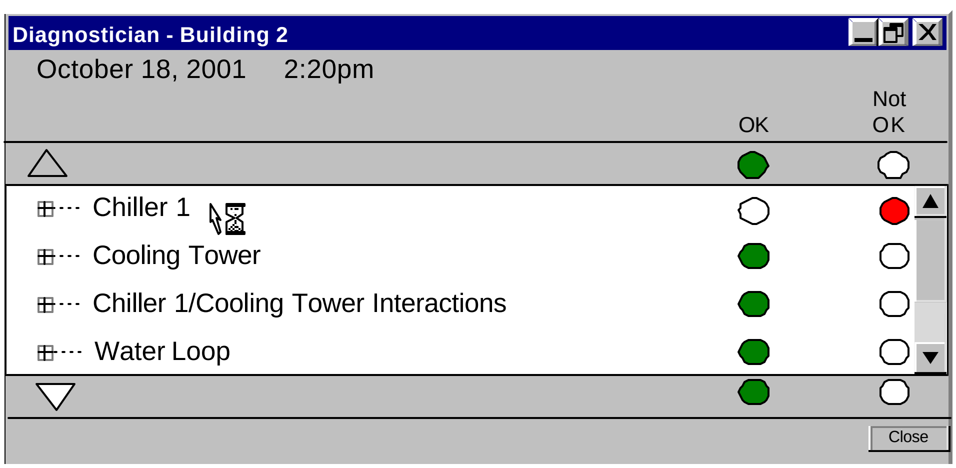


Figure 6 Recommended Layout for Systems Window

3.5.1.18 The condition window shall list the current status of all diagnostics for a specific subsystem. A recommended layout for this window is depicted in Figure 7.

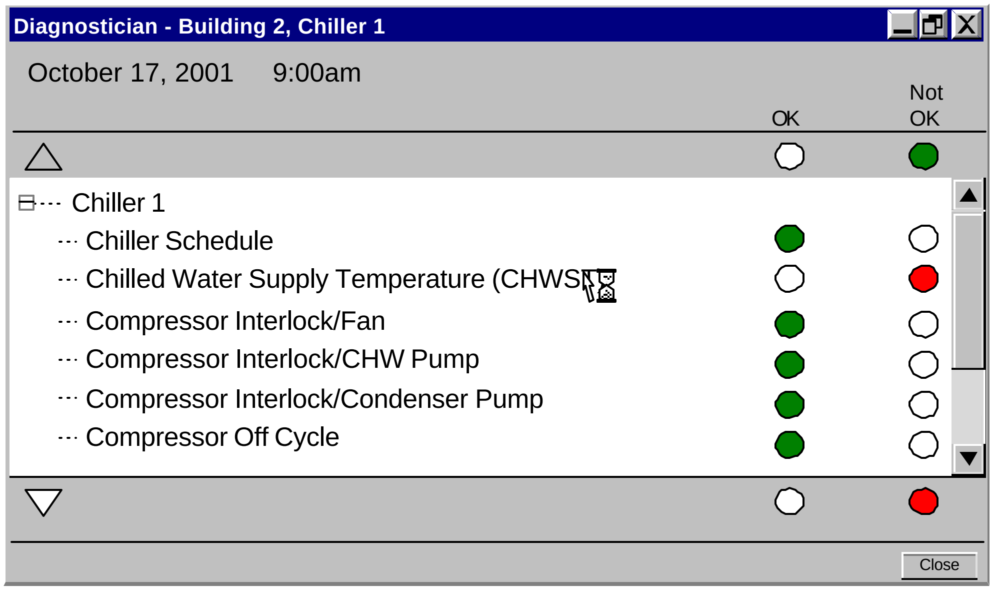


Figure 7 Recommended Layout for Condition Window

3.5.1.19 The diagnostic information window shall provide a detailed description of the diagnostic. A recommended layout for this window is depicted in Figure 8.

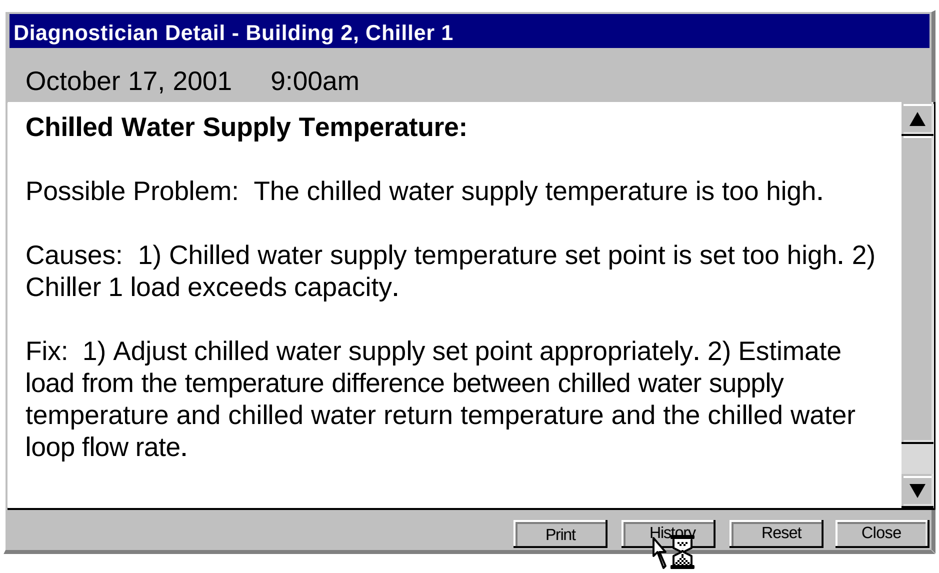


Figure 8 Recommended Layout for Diagnostic Information Window

3.5.1.20 The diagnostic information window shall have a button labeled “Print” that when clicked will display a window listing items to print including the diagnostic information window, the history window, and both the diagnostic and history windows. The user selects the item of interest and clicks the “OK” button to print the selection, an image(s) of the item(s) selected.

3.5.1.21 The diagnostic information window shall include the following information regarding the diagnostic:

1. A description of the possible problem.
2. Potential causes.
3. Fixes.

3.5.1.22 The diagnostic information window shall have a button labeled “Close” that shall dismiss the window.

3.5.1.23 The diagnostic information window shall have a button labeled “History” that when clicked will display the diagnostic history window and display the previous week’s diagnostic results.

3.5.1.24 The diagnostic history window shall display historical diagnostic results for a specific diagnostic. A recommended layout for this window is depicted in **Error! Reference source not found.**. This figure includes a color map that provides a graphical indication of diagnostic condition.

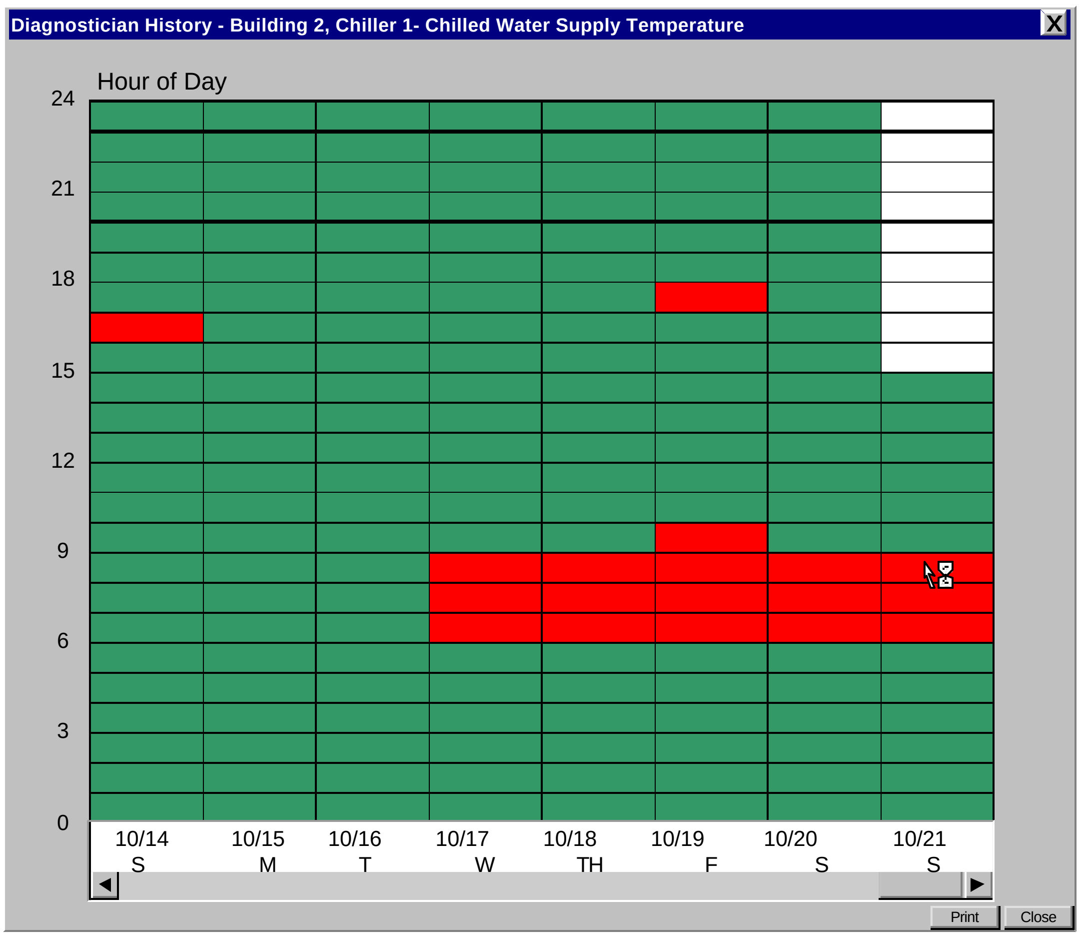


Figure 9 Recommended Layout for Diagnostic History Window

3.5.1.25 The diagnostic history window shall provide user selections for start times and end times for the history interval. These selections shall be in the form of a calendar control.

3.5.1.26 The smallest time interval displayed by the diagnostic history window is one week.

3.5.1.27 The longest time interval that may be displayed by the diagnostic history window is two years.

3.5.1.28 The color map of the history window shall indicate confirmed faults with the color red, potential faults with the color yellow, normal conditions with the color green, and periods when diagnostic processing was not active with the color gray. Diagnostic processing should be assumed inactive between periods of time when no confirmed fault, potential fault, or normal condition has been recorded.

3.5.1.29 The vertical axis of the color map of the history window shall indicate hour of the day and the horizontal axis shall indicate the absolute date and the day of week.

3.5.1.30 The diagnostic history window shall have a button labeled “Print” that when clicked will display a window listing items to print including the diagnostic information window, the history window, and both the diagnostic and history windows. The user selects the item of interest and clicks the “OK” button to print the selection, an image(s) of the item(s) selected.

3.5.1.31 The diagnostic history window shall have a button labeled “Close” that will dismiss the window.

3.5.1.32 The subsystems window, condition window, and diagnostic information window shall display a title that indicates its specific location or absolute path in the navigation hierarchy of windows. This title shall be a concatenation of the title of the previous window displayed, not including the diagnostic history window, and the name of the entry selected to obtain the current window. The two parts of the title shall be separated by a dash surrounded by a single space.

3.5.1.33 The main window, subsystems window, condition window, and diagnostic information window shall display the appropriate time below the title as specified in 3.3.1.3.

3.5.1.34 The main window, subsystems window, and condition window shall have three diagnostic indicators for each item listed.

3.5.1.35 One indicator shall be active when no diagnostic conditions exists. This indicator shall be designated the “OK” indicator and shall appear green when active.

3.5.1.36 One indicator shall be active when a potential diagnostic condition exists. This indicator shall be designated the “Caution” and shall appear yellow when active.

3.5.1.37 One indicator shall be active when a confirmed diagnostic condition exists. This indicator shall be designated the “Not OK” indicator and shall appear red when active.

3.5.1.38 Only one indicator shall be active at a given time for a specific diagnostic and no indicators shall flash when active.

3.5.1.39 The diagnostic indicators on the main window and subsystems window shall summarize all diagnostic conditions associated with each entry in the window. In general, an active “OK” indicator indicates no positive diagnostic results currently exist within the building or subsystem, as applicable for the window. An active “Caution” indicator indicates that at least one potential problem currently exists within the building or subsystem, as applicable, and no confirmed problem currently exists. An active “Not OK” indicator indicates at least one confirmed problem exists regardless of whether cautionary or non-positive results exist. Essentially, confirmed problems override potential problem indications which override non-positive results.

3.6 Security

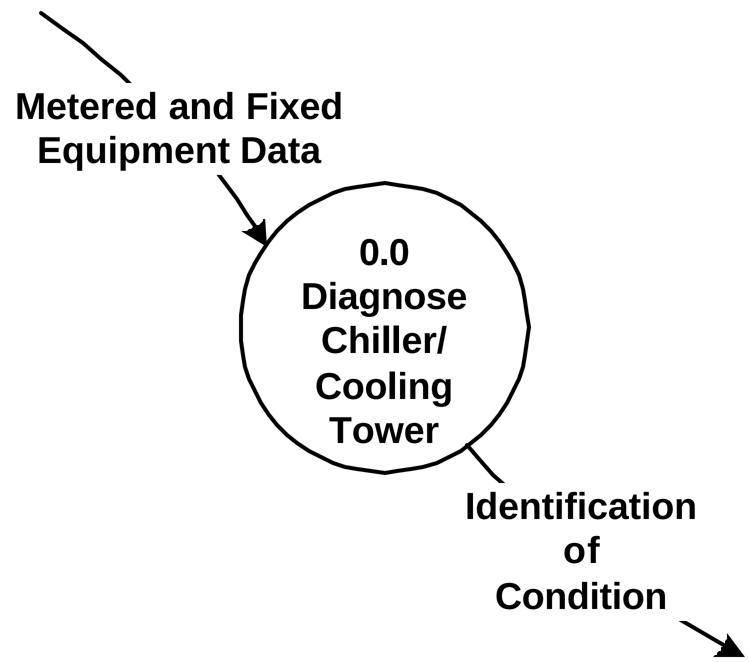
Certain functions of the tool directly available to the user require the user to possess supplementary privileges associated with performing these functions. These supplementary privileges are possessed by the administrator user and are in addition to those of the general user as described in 2.5. The tool determines the type of user by requesting an identifier and password from the user. The requirements related to this process are discussed in other requirements in this document.

3.7 Other Requirements

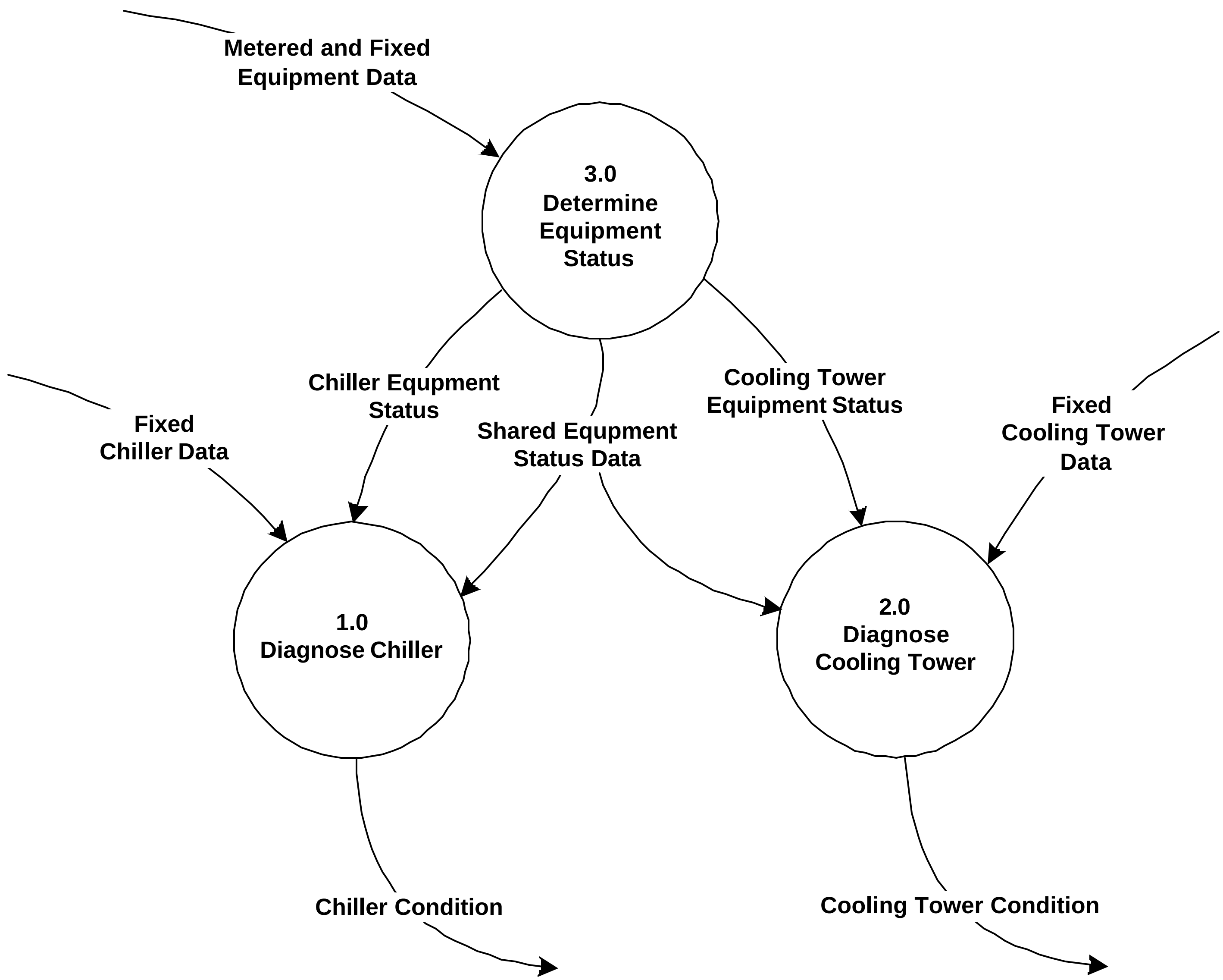
The tool shall log to permanent storage the occurrence of changes to the fixed data. The log shall indicate the time and date of the change, original value of the item(s) changed, and the new value of the item(s) changed.

4. Appendix A: Data Flow Diagrams of Diagnostic Processes for Chillers, Cooling Towers, and Chilled-Water Distribution

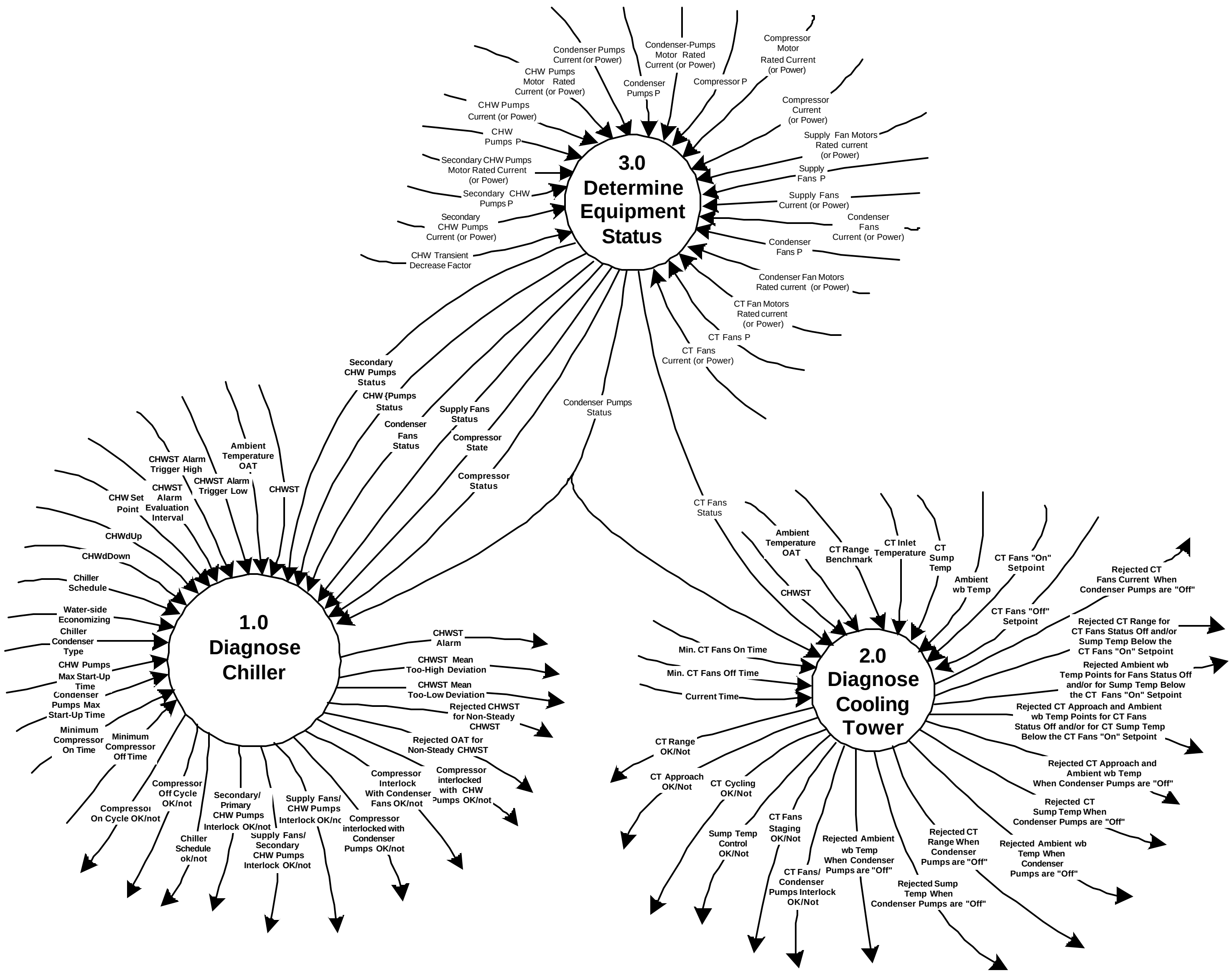
Context Diagram
Diagnose Chiller/Cooling Tower



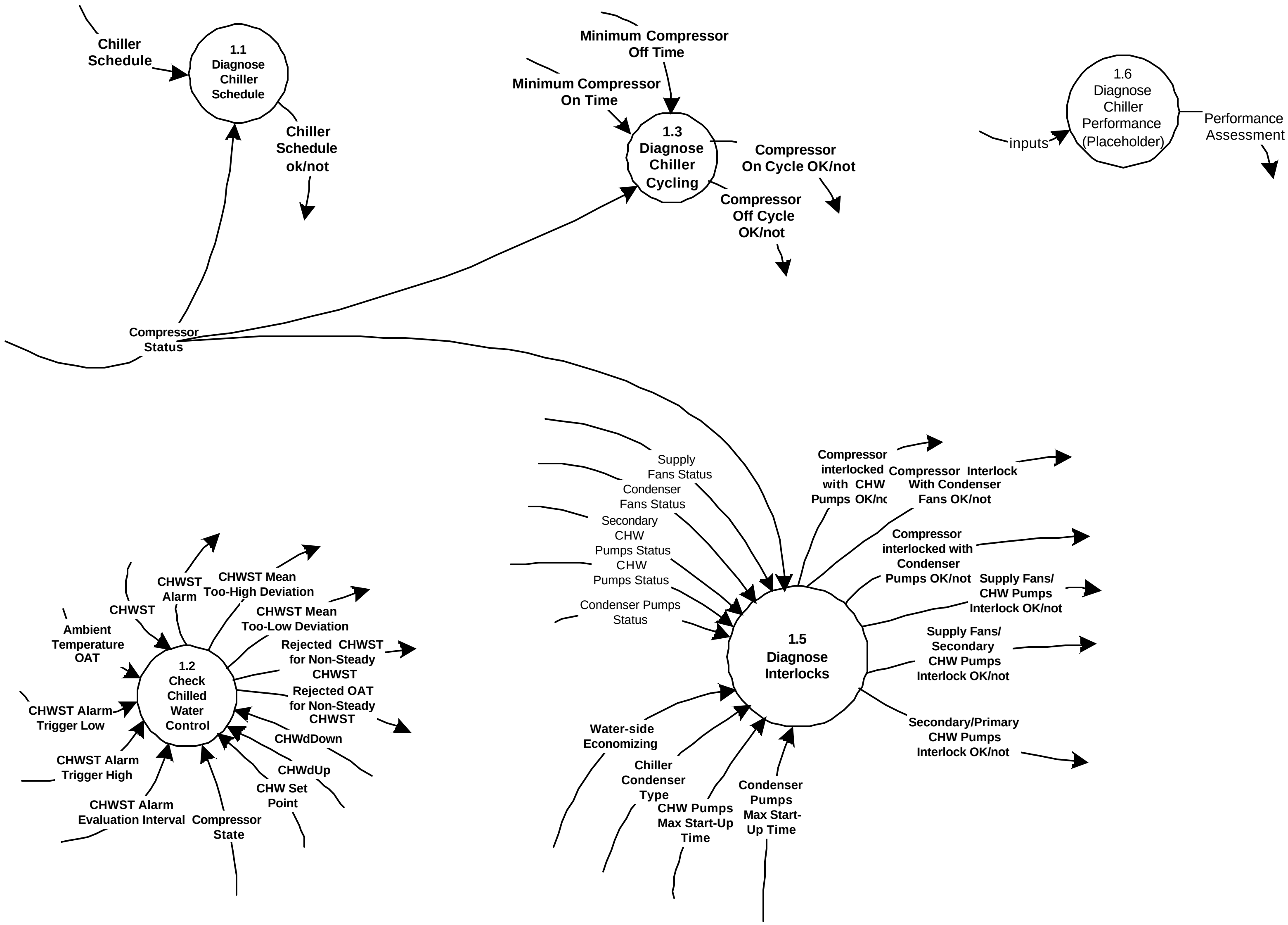
0.0 Diagnose Chiller/Cooling Tower



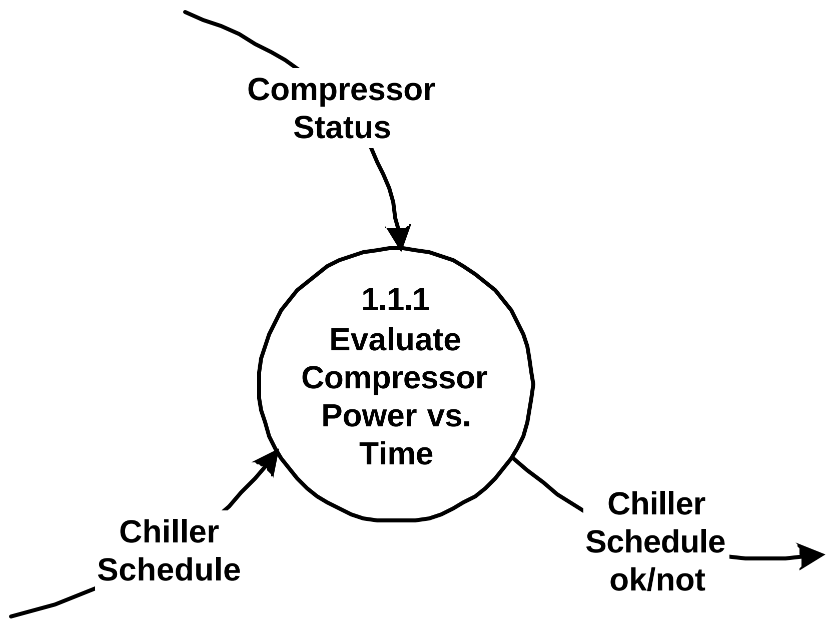
0.0 Diagnose Chiller/Cooling Tower



1.0 Diagnose Chiller



1.1 Diagnose Chiller Schedule



1.1.1 Evaluate Compressor Power vs. Time

Compare the current time to the scheduled time for the chiller to be on.,

If the current time is a scheduled chiller "on" time, then stop--make no further check. OK.

If the current time is outside the scheduled chiller "on" times (i.e., the chiller should be off), then check if the Compressor Status = "Off."

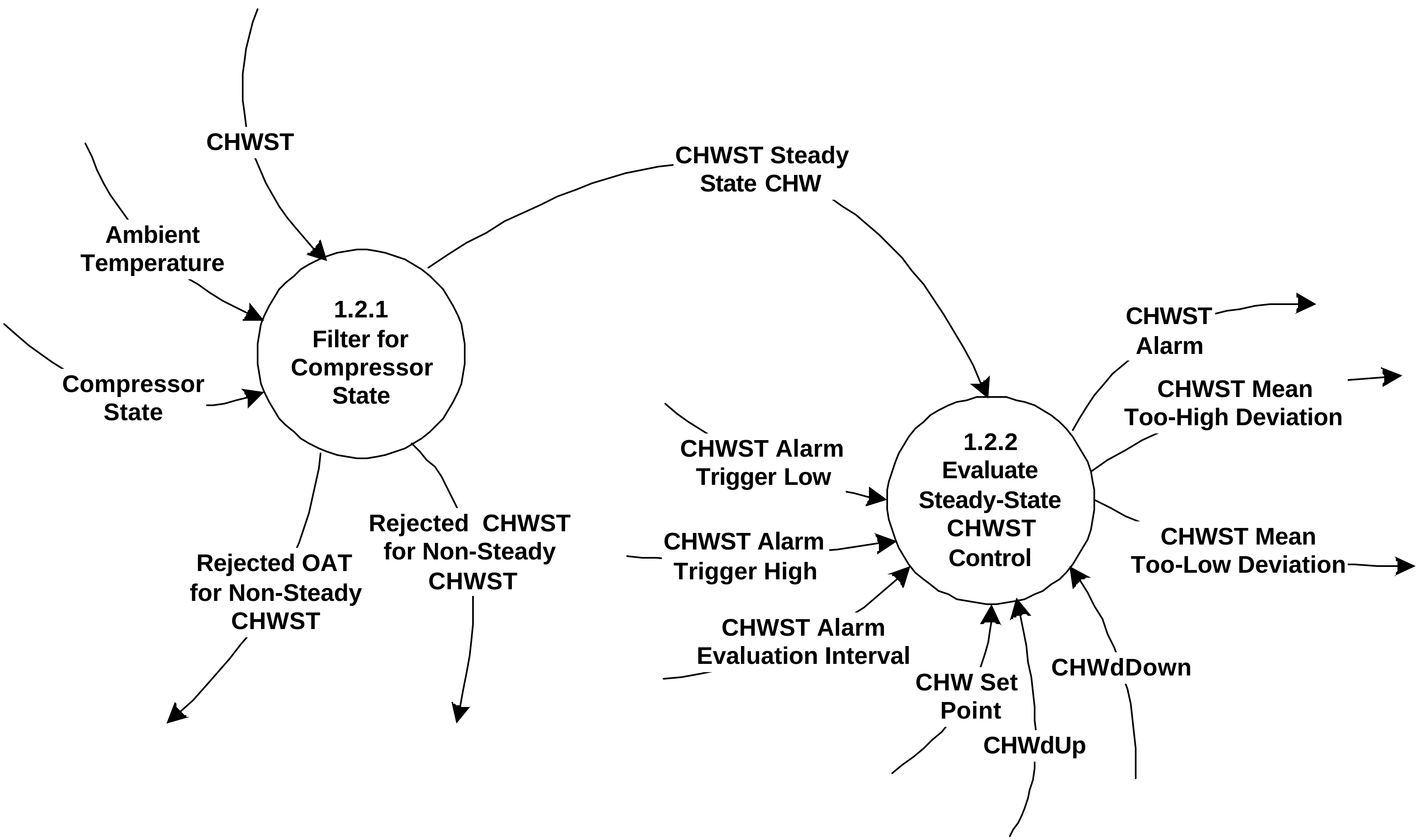
If the Compressor Status = "Off," then the chiller is off as it should be and it is OK. Set Chiller Schedule OK/Not = "OK".

If the Compressor Status = "On," then the Chiller is "On" when it should be off. Not OK. Energy is being wasted. Set Chiller Schedule OK/Not = "Not OK"

Note: The purpose of this process is to determine if the chiller is on when it is supposed to be off.

Ref. File: 1.2 Chiller schedule diagnostics.doc

1.2 Check Chilled Water Control

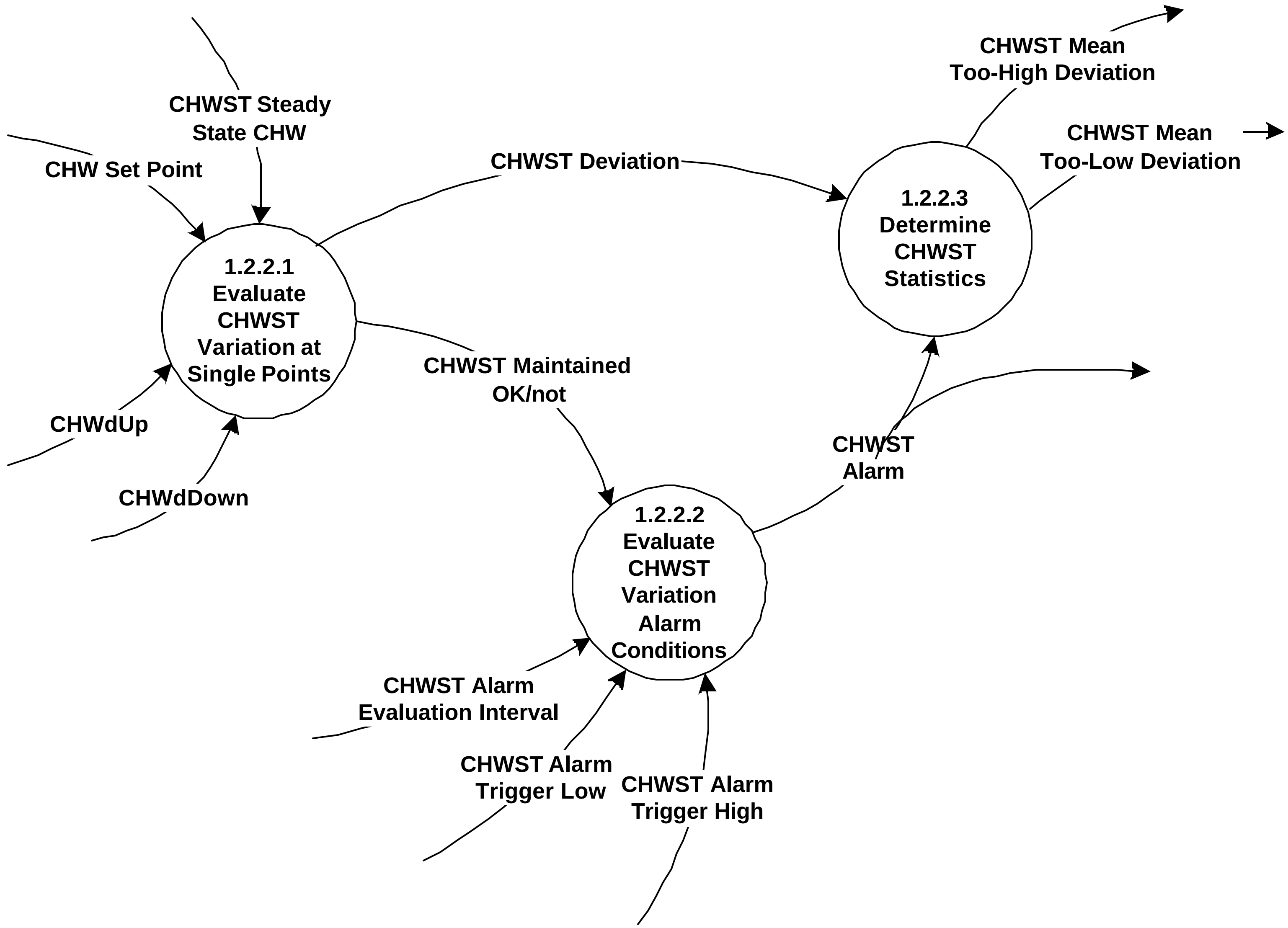


1.2.1 Filter (pass) CHWST Steady State "On" Only

If Compressor State = "Steady", then pass values of CHWST.
Label these passesd values CHWST Steady State CHW.

If Compressor State = "Transient" or Compressor State = "Off", then reject values of CHWST.

1.2.2 Evaluate Steady-State CHWST Control



1.2.2.1 Evaluate CHWST Variation at Single Points

Calculate the upper bound for acceptable Chilled Water Temperature using

CHWST Upper Bound = CHW Setpoint + (CHWdUp)

Calculate the acceptable lower bound for the Chilled Water Temperature using

CHWST Lower Bound = CHW Setpoint - (CHWdDown).

Compare the Chilled Water Supply Temperature (CHWST) for steady state to the CHWST Upper Bound and CHWST Lower Bound.

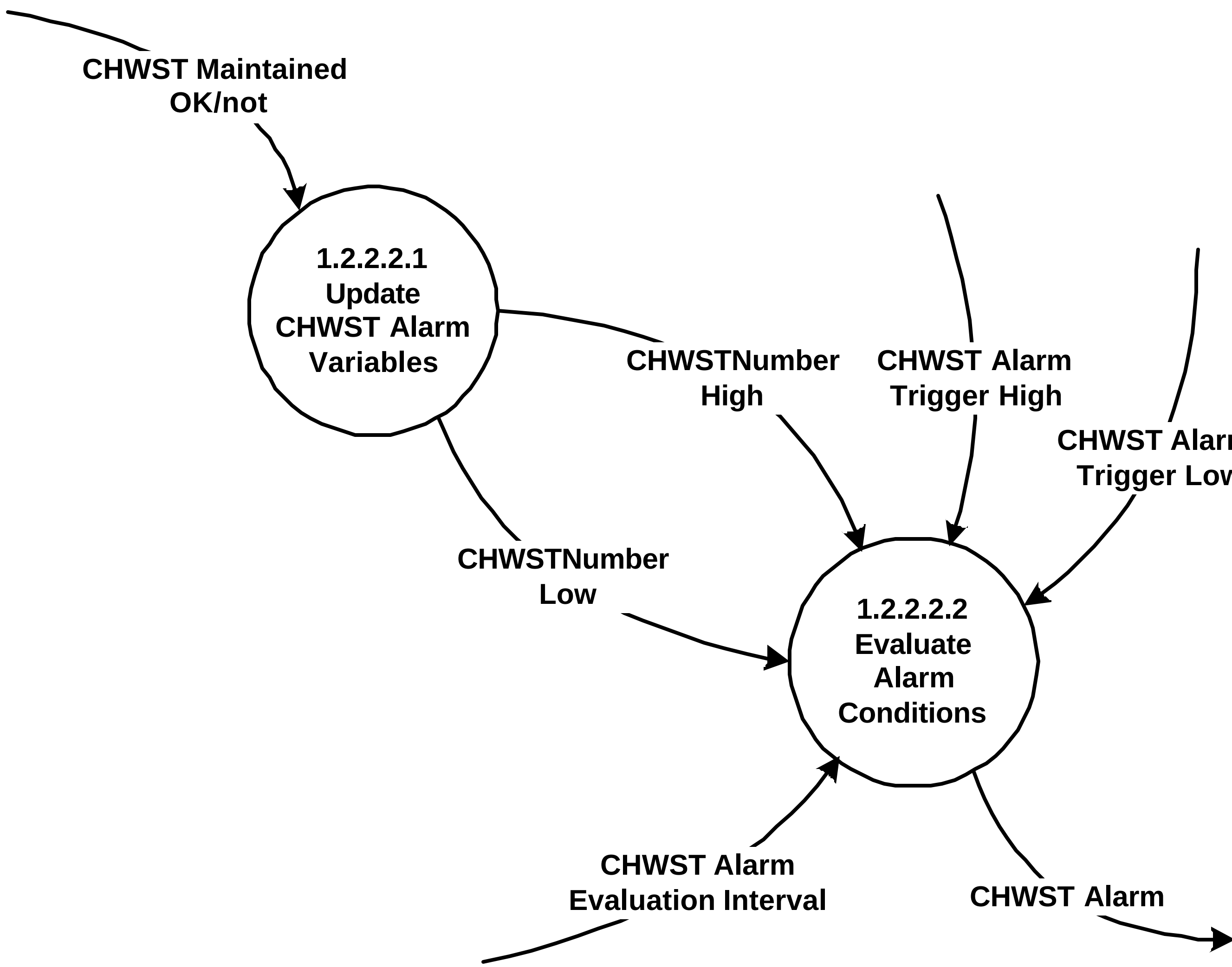
If CHWST Steady State CHW > CHWST Upper Bound, then
set CHWST Maintained OK/not = "Too high" for the current time.
If CHWST Steady State CHW <= CHWST Upper Bound
and CHWST Steady State CHW>= CHW Lower Bound, then
set CHWST Maintained OK/not = "OK" for the current time.
If CHWST Steady State CHW < CHWST Lower Bound, then
set CHWST Maintained OK/not = "Too low" for the current time.

Calculate the CHW Temperature Deviation for a single point (current time)

CHWST Deviation = CHWST Steady State CHW - CHW Setpoint.

Ref file: 2.1CHW temperature control.doc

1.2.2.2 Evaluate CHWST Variation Alarm Conditions



1.2.2.2.1 Update CHWST Alarm Variables

Update the variable CHWST Maintained OK/not Array

Update all values in the array, adding the current value of CHWST Maintained OK/not to the array and by dropping the oldest value of CHWST Maintained OK/not from the array.

Update values for CHWSTNumber High and CHWSTNumber Low.

Set CHWSTNumber High = number of values "Too High" appearing in CHWST Maintained OK/not Array.

Set CHWSTNumber Low = number of values "Too Low" appearing in CHWST Maintained OK/not Array.

[Determine whether this evaluation should be done during initial start-up processing (this shouldn't really be part of the DFDs because it represents intialization and control),

If Total Number of Time Steps Processed < CHWST Alarm Evaluation Interval, then terminate processing of 2.8.2 (i.e., do not evaluate CHWST Variation Alarm Conditions).

Otherwise, continue with 2.8.2 processing.]

Ref file: 2.1CHW temperature control.doc

1.2.2.2.2 Evaluate Alarm Conditions

Calculate values for CHWSTFraction High and CHWSTFraction Low.

CHWSTFraction High = CHWSTNumber High/(CHWST Alarm Evaluation Interval)

CHWSTFraction Low = CHWSTNumber Low/(CHWST Alarm Evaluation Interval)

Compare CHWSTFraction High with CHWST Alarm Trigger High.
Compare CHWSTFraction Low with CHWST Alarm Trigger Low.

If CHWSTFraction High >= CHWST Alarm Trigger High, then
set CHWST Alarm = "Too High."
If CHWSTFraction High < CHWST Alarm Trigger High and CHWSTFraction Low < CHWST Alarm Trigger Low, then
set CHWST Alarm = "OK".
If CHWSTFraction Low >= CHWST Alarm Trigger Low, then
set CHWST Alarm = "Too Low."

Notes: Conclusions regarding a fault existing or not based on individual points are likely to be unrealiable. Conclusions are likely to best be made by considering a high percentage of points over some period of time exceeding some minimum time, e.g., a day or a week (24 hours or 168 hours). Therefore, we base the assignment of CHWST Alarm on a minimum set of points rather than individual points.

Ref file: 2.1CHW temperature control.doc

1.2.2.3 Determine CHWST Statistics*

If CHWSTAlarm = Too High, then

Calculate mean CHWST for the times correspoding to the too-high points in the CHWST Maintained OK/not Array.

CHWST Mean Too-High Deviation = Sum [CHWST Deviation(time index)]/ (CHWSTNumber High),

where time index takes values between the currrent time and (CHWST Alarm Evaluation Interval - 1) time steps ago and the sum only includes values of CHWST Deviation for which CHWST Maintained OK/not = "Too High".

Set Mean Too Low CHWST Deviation = null.

If CHWSTAlarm = Too Low, then

Calculate mean CHWST for the times correspoding to the too-low points in the CHWST Maintained OK/not Array.

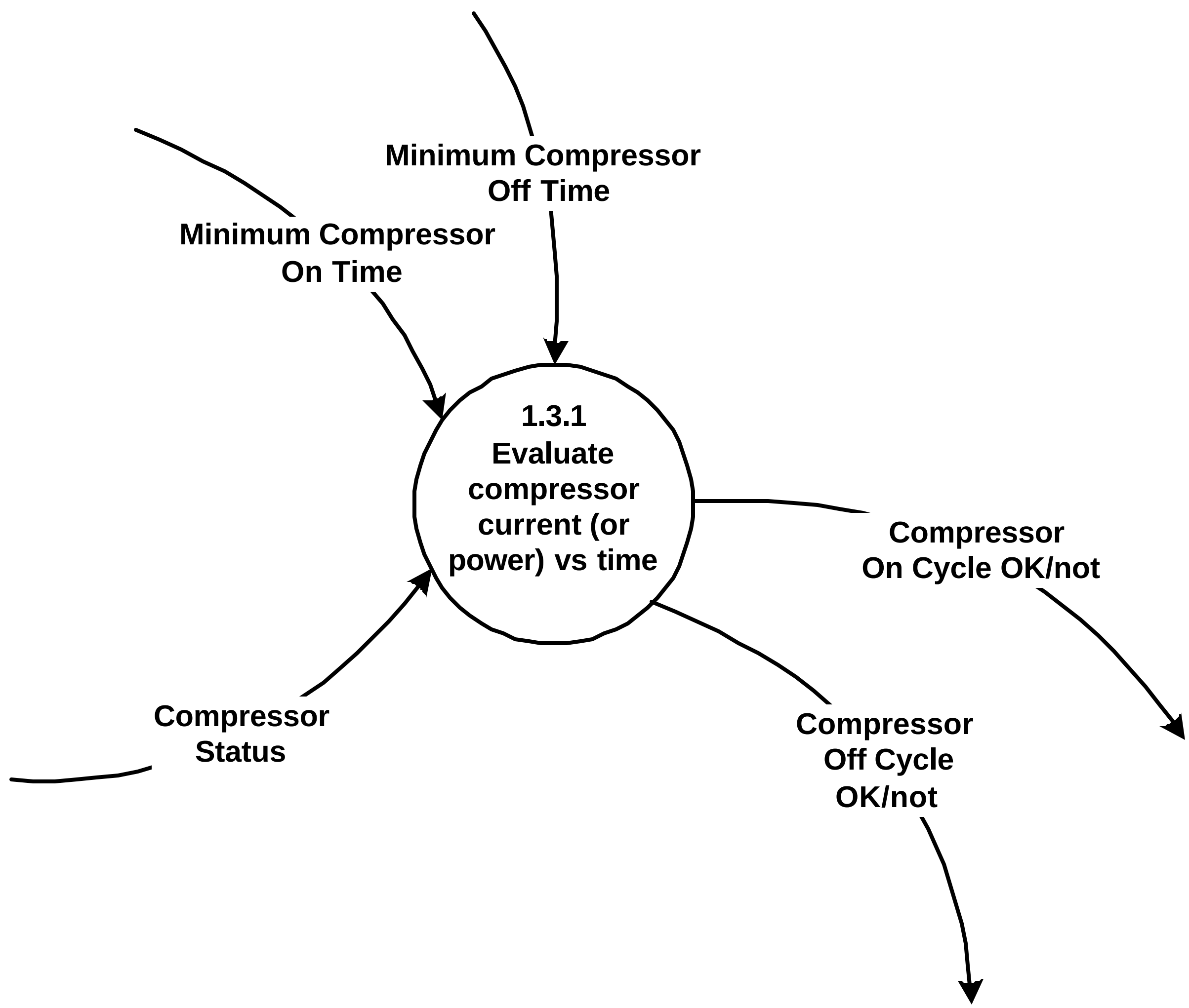
CHWST Mean Too-Low Deviation = Sum [CHWST Deviation(time index)]/ (CHWSTNumber Low),

where time index takes values between the currrent time and (CHWST Alarm Evaluation Interval - 1) time steps ago and the sum only includes values of CHWST Deviation for which CHWST Maintained OK/not = "Too Low".

Set Mean Too High CHWST Deviation = null.

Note: This process is proposed for Round 2. Also, additional or other statistics could be calculated in this process. These should also be proposed for Round 2.

1.3 Diagnose Chiller Cycling



1.3.1 Evaluate Compressor current (or power) vs time

If Compressor Status = "On" and Last Compressor Status = "On", then terminate this evaluation. Nothing new to check.

If Compressor Status = "On" and Last Compressor Status = "Off," then set Last Compressor Switch On Time = Current Time and check Last Compressor Off Interval.

Calculate the Last Compressor Off Interval using

Last Compressor Off Interval = Last Compressor Switch On Time - Last Compressor Switch Off Time

If Last Compressor Off Interval >= Minimum Compressor Off Time, then set Compressor Off Cycle OK/not = "OK."

If Last Compressor Off Interval < Minimum Compressor Off Time, then set Compressor Off Cycle OK/not = "not OK." The compressor is not staying off long enough during cycling. Possible causes include an incorrectly specified minimum off time in the control algorithm or for compressors with minimum on/off times controlled by a relay a failed relay or one requiring adjustment.

If Compressor Status = "Off" and Last Compressor Status = "Off," then terminate this evaluation. Nothing new to check.

If Compressor Status = "Off" and Last Compressor Status = "On", then set Last Compressor Switch Off Time = Current Time and check Last Compressor On Interval.

Calculate the Last Compressor On Interval using

Last Compressor On Interval = Last Compressor Switch Off Time - Last Compressor Switch On Time

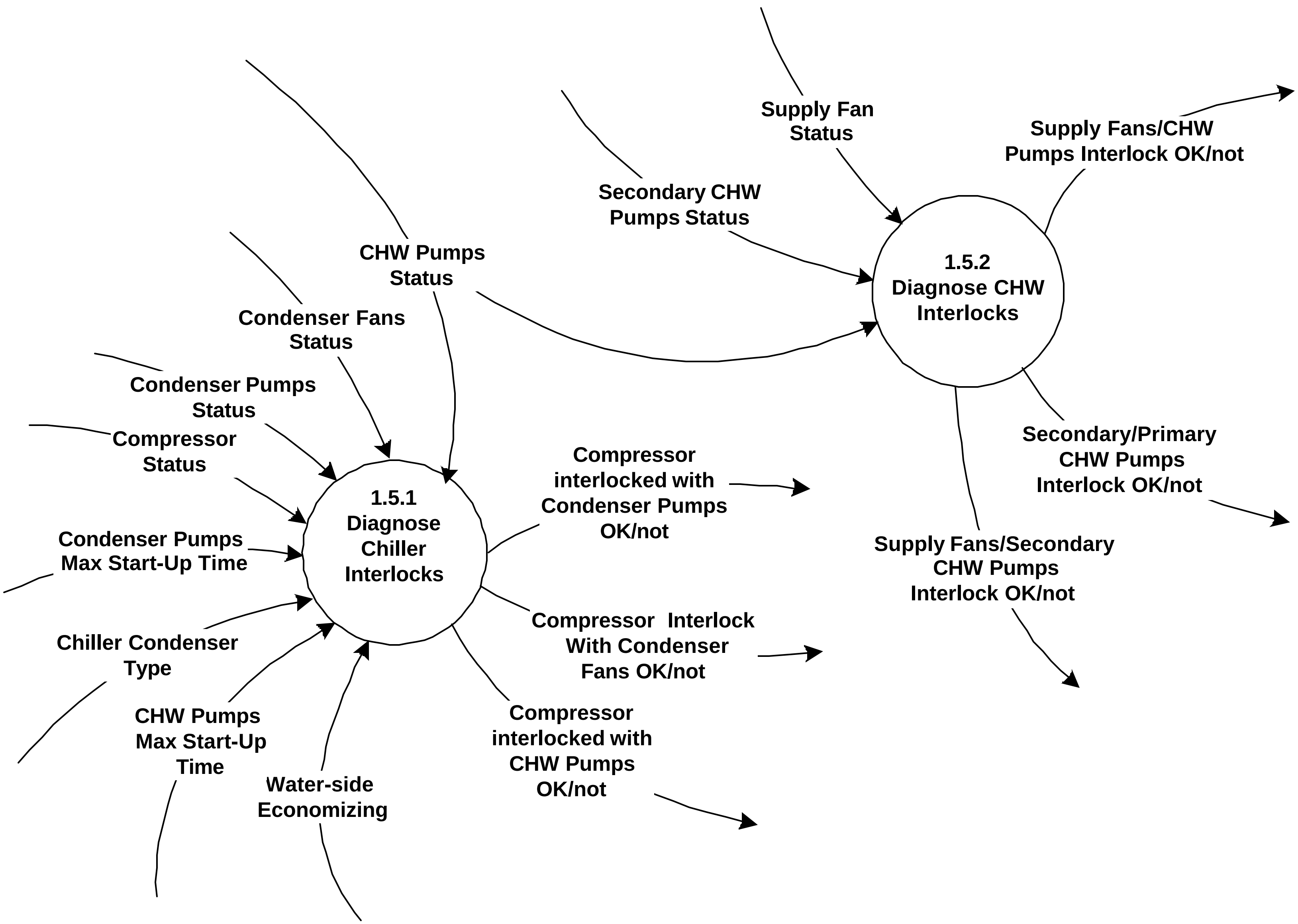
If Last Compressor On Interval >= Minimum Compressor On Time, then Compressor On Cycle OK/not = "OK."

If Last Compressor On Interval < Minimum Compressor On Time, then Compressor On Cycle OK/not = "not OK." The compressor is not staying on long enough during cycling. Possible causes include an incorrectly specified minimum on time in the control algorithm or for compressors with minimum on/off times controlled by a relay a failed relay or one requiring adjustment.

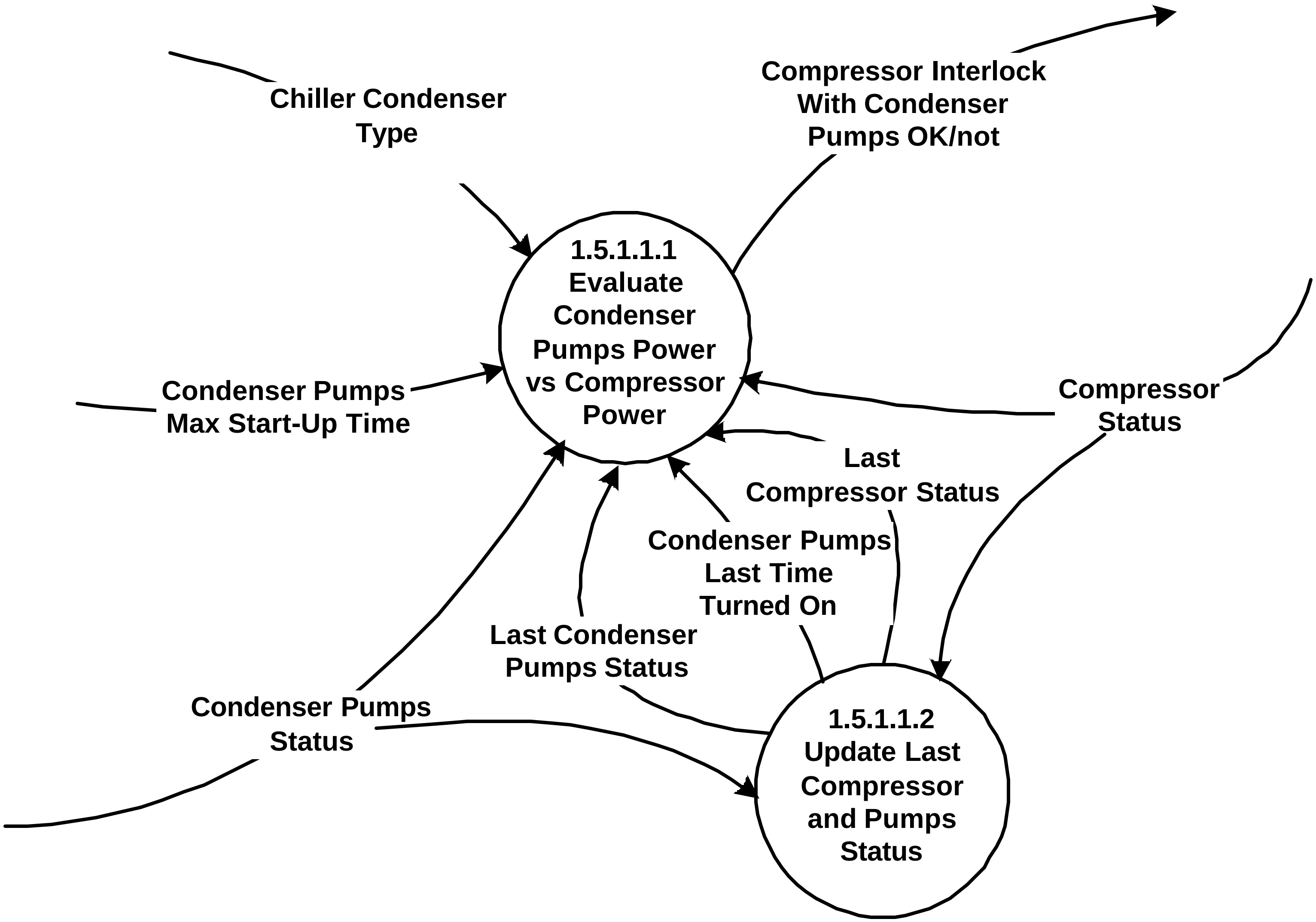
Update Last Compressor Status : Set Last Compressor Status = Compressor Status*

*This over-writes previous compressor status with current status and should not be performed if previous status is required in subsequent processing.
Ref: 4.x chiller cycling.doc

1.5.0 Diagnose Interlocks



1.5.1.1 Verify Proper Condenser Pumps/Compressor Interlock



1.5.1.1.1 Evaluate Condenser Pumps Power vs Compressor Power

If Chiller Condenser Type = Air-Cooled, then terminate this analysis.

If Chiller Condenser Type = Water-cooled, then

compare the compressor status and condenser-pumps status for the current time.

If the Compressor Status = "On" and the Condenser-Pumps Status = "On," then Compressor Interlock With Condenser Pumps OK/not = "OK"

If the Compressor Status = "Off" and the Condenser-Pumps Status = "Off," then Compressor Interlock With Condenser Pumps OK/not = "OK," unless

the Compressor Status = "Off" and Last Compressor Status = "Off," and current Condenser Pumps Status = "Off" and Last Condenser Pumps Status = "On", then the condenser pumps are cycling (turning on and off) unnecessarily and Compressor Interlock With Condenser Pumps OK/not = "Not OK. Repeated frequent cycling will shorten the life of the condenser pumps."

If the Compressor Status = "On" and the Condenser-Pumps Status = "Off," then Compressor Interlock With Condenser Pumps OK/not = "not OK." The chiller cannot reject heat and this could result in damage to the compressor.

If the Compressor Status = "Off" and the Condenser-Pumps Status = "On," then further evaluation is required

.

If Current Time - Condenser Pumps Last Time Turned On <= Condenser Pumps Max Start-Up Time,then Compressor Interlock With Condenser Pumps OK/not = "OK" (for now; actually this corresponds to no fault detected).

If Current Time - Condenser Pumps Last Time Turned On > CondenserPumps Max Start-Up Time, then Compressor Interlock With Condenser Pumps OK/not = "Not OK." The condenser pumps are turning on too much in advance of the chiller and wasting energy.

1.5.1.1.2 Update Last Compressor and Pumps Status

If Condenser Pumps Status = "On" and Last Condenser Pumps Status = "Off", then
set Condenser Pumps Last Time Turned On = Current Time.

Otherwise, do not change Condenser Pumps Last Time Turned On, i.e.,
set Condenser Pumps Last Time Turned On = Condenser Pumps Last Time Turned On.

Then,

Set Last Compressor Status = Compressor Status.*

Set Last Condenser-Pumps Status = Condenser-Pumps Status.*

*These actions over-write the previous statuses and should not be performed if the previous statuses are required in subsequent processing.

1.5.1.2.1 Evaluate Condenser Fans Power vs Compressor Power

If Chiller Condenser Type = Water-Cooled, terminate this analysis.

If Chiller Condenser Type = Air-cooled, then

Compare the compressor status and condenser-fan status for the current time.

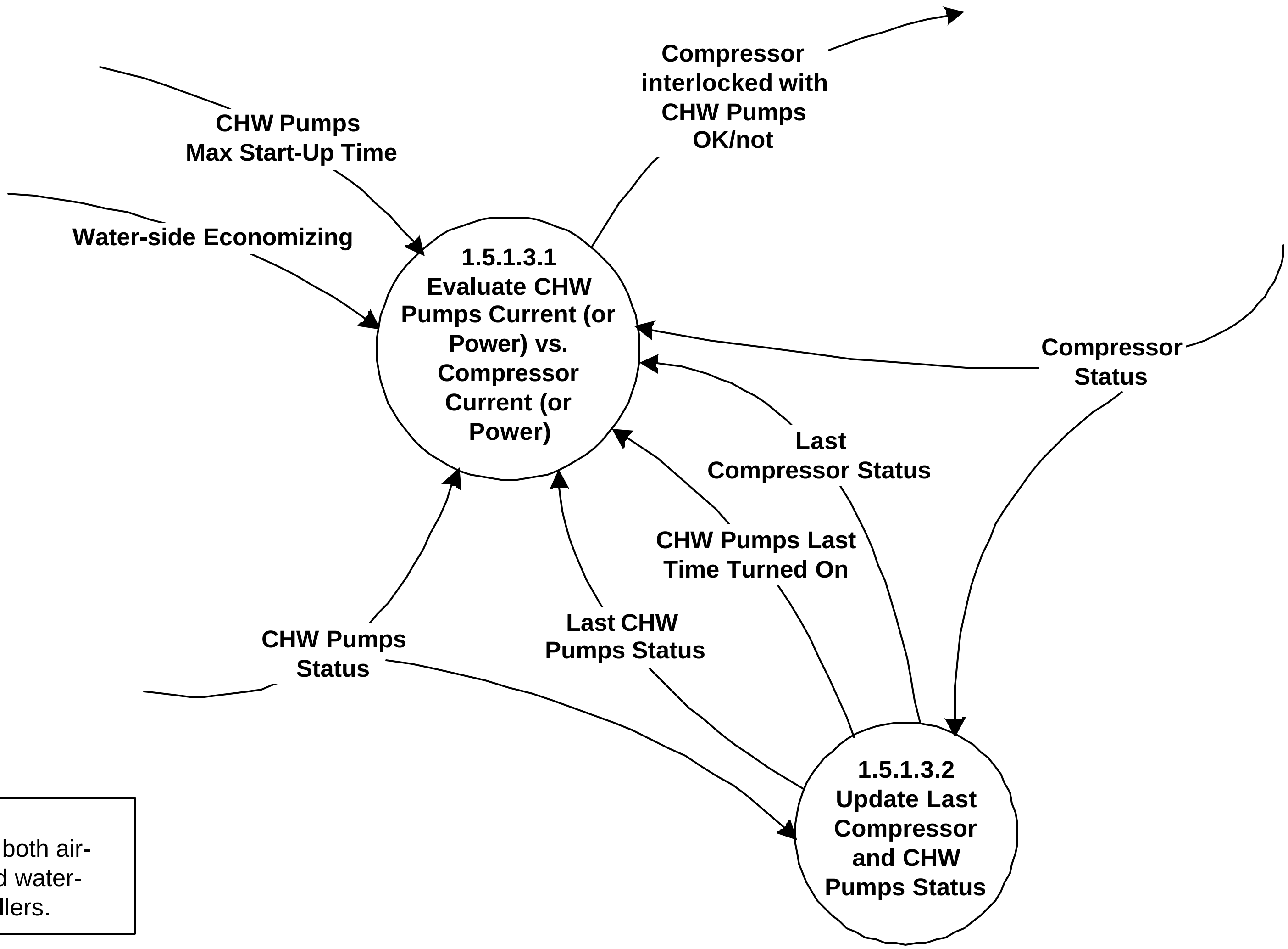
If the Compressor Status = "On" and the Condenser-Fans Status = "On," then Compressor Interlock With Condenser Fans OK/not = "OK"

If the Compressor Status = "Off" and the Condenser-Fans Status = "Off," then Compressor Interlock With Condenser Fans OK/not = "OK."

If the Compressor Status = "On" and the Condenser-Fans Status = "Off," then Compressor Interlock With Condenser Fans OK/not = "Not OK." The chiller cannot reject heat and this could result in damage to the compressor.

If the Compressor Status = "Off" and the Condenser-Fans Status = "On," then Compressor Interlock With Condenser Fans OK/not = "Not OK." The fans are running unnecessarily and wasting energy.

1.5.1.3 Verify Proper CHW Pumps/ Compressor Interlock



Note:
Applies to both air-cooled and water-cooled chillers.

1.5.1.3.1 Evaluate Chilled Water Pumps Power vs. Compressor Power

Compare the chiller status and chilled water pumps status for the current time.

If the Compressor Status = "On" and the CHW Pumps Status = "On," then Compressor Interlock With CHW Pumps OK/not = "OK"

If the Compressor Status = "Off" and the CHW Pumps Status = "Off," then Compressor Interlock With CHW Pumps OK/not = "OK," unless

the Compressor Status= "Off" and Last Compressor Status = "Off," and current CHW Pumps Status = "Off" and Last CHW Pumps Status = "On", then the condenser pumps are cycling (turning on and off) unnecessarily and Compressor Interlock With CHW Pumps OK/not = "Not OK." Repeated frequent cycling will shorten the life of the CHW Pumps.

If the Compressor Status = "On" and the CHW-Pumps Status = "Off," then Compressor Interlock With CHW Pumps OK/not = "not OK." The chiller is operating without a load. Energy is being wasted and damage to the chiller may result.

If the Compressor Status = "Off" and the CHW-Pumps Status = "On," then further evaluation is required.

If Water-Side Economzing = "Yes", then Compressor Interlock With Condenser Pumps OK/not = "OK" (as far as we can tell).

If Water-Side Economzing = "No", and

If Current Time - CHW Pumps Last Time Turned On <= CHW Pumps Max Start-Up Time, then Compressor Interlock With CHW Pumps OK/not = "OK" (for now; actually this corresponds to no fault detected).

If Current Time - CHW Pumps Last Time Turned On > CHW Pumps Max Start-Up Time, then Compressor Interlock With CHW Pumps OK/not = "Not OK." The CHW pumps are turning on too much in advance of the chiller and wasting energy.

Note: Applies to both water-cooled and air-cooled chillers.

Ref. File: 5.3.2 CHW Pumps interlock.doc

1.5.1.3.2 Update Last Compressor and CHW Pumps Status

If CHW Pumps Status = "On" and Last CHW Pumps Status = "Off", then
set CHW Pumps Last Time Turned On = Current Time.

Otherwise, do not change CHW Pumps Last Time Turned On, i.e.,
set CHW Pumps Last Time Turned On = CHW Pumps Last Time Turned On.

Then,

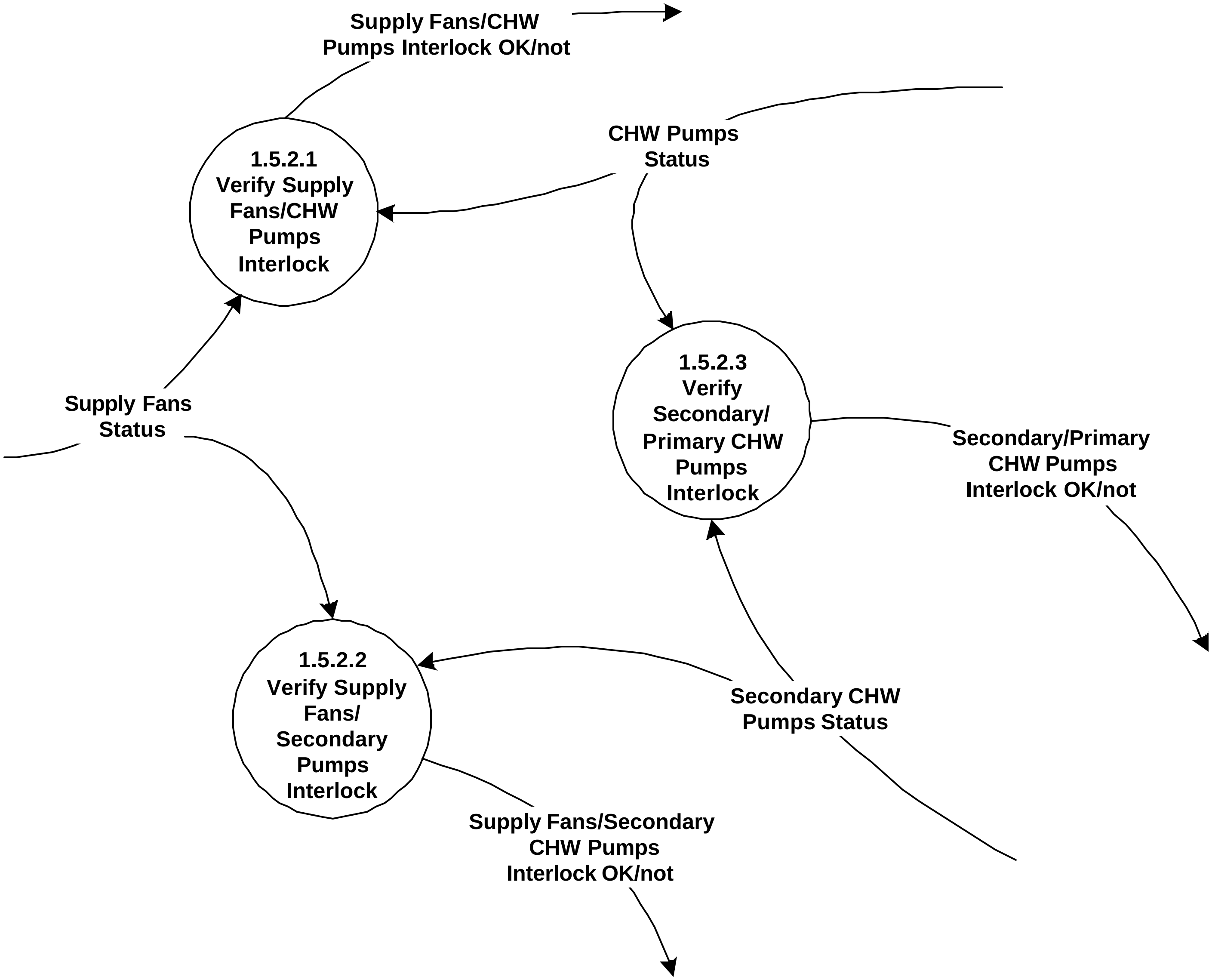
set Last Compressor Status = Compressor Status.*

and

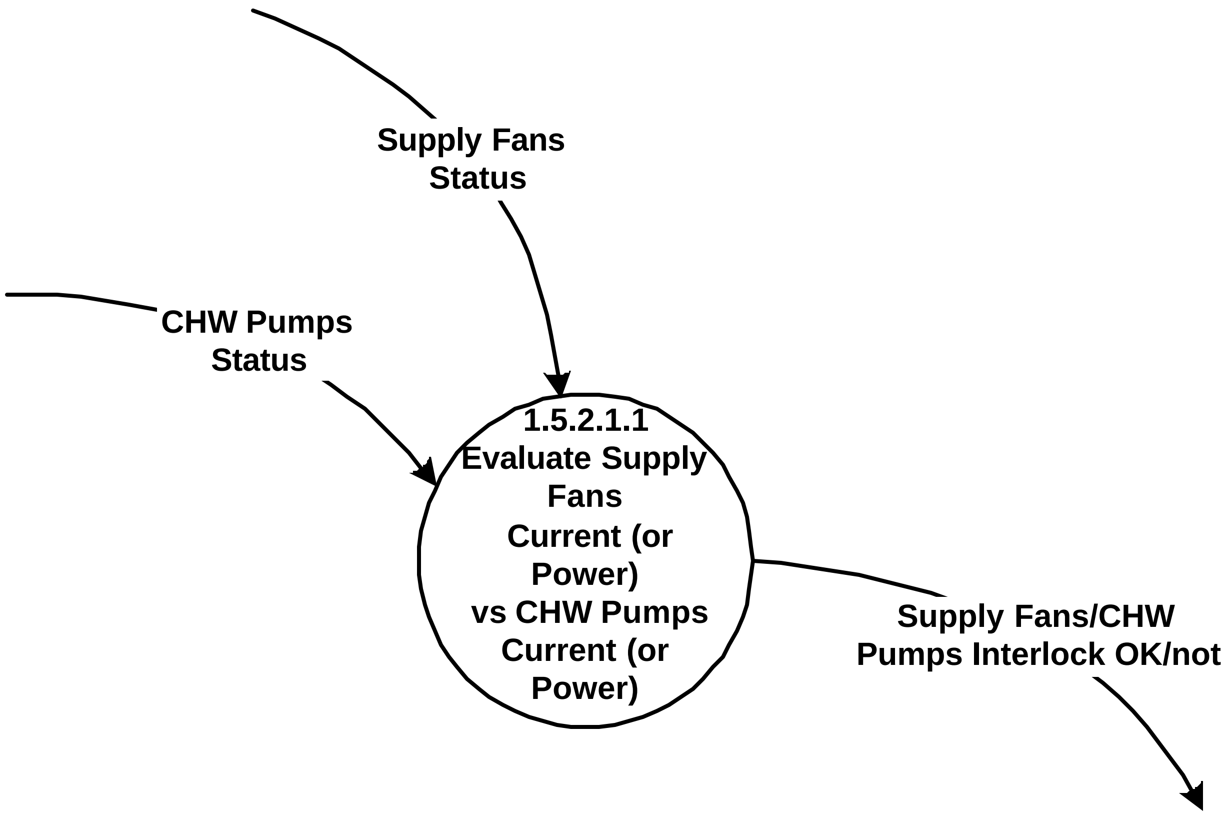
set Last CHW Pumps Status = CHW Pumps Status.

*This overwrites the previous status and should not be performed if subsequent processing requires the previous status.

1.5.2 Diagnose CHW Interlocks



1.5.2.1 Verify Supply Fans/CHW Pumps Interlock



1.5.2.1.1 Evaluate Supply Fans Current (or Power) vs Primary CHW Pumps Current (or Power)

For each set of primary CHW Pumps, Compare the CHW Pumps Collective Status and Supply Fan Status for the supply fans for each air handler served by this set of specific CHW Pumps.

If the CHW Pumps Collective Status = "On" and the Supply Fan Status = "On" for at least one of the air handlers served by this CHW Pumps, then set the Supply Fans/CHW Pumps Interlock OK/not for this set of CHW Pumps = "OK."

If the CHW Pumps Collective Status = "Off" and the Supply Fan Status = "Off" for all of the air handlers served by this set of CHW Pumps, then set the Supply Fans/CHW Pumps Interlock OK/not for this CHW Pumps="OK."

If the CHW Pumps Collective Status = "Off" and the Supply Fan Status = "On" for at least one of the air handlers served by this set of CHW Pumps, then set the Supply Fans/CHW Pumps Interlock OK/not for this set of CHW Pumps = "Possible problem with supply fan control--check to see if loads in the spaces served are being met for supply fans with Supply Fans Status = "On" that are part of air handlers served by these CHW Pumps. Occupant complaints about temperature or stuffiness may be in indicator of the load not being met.

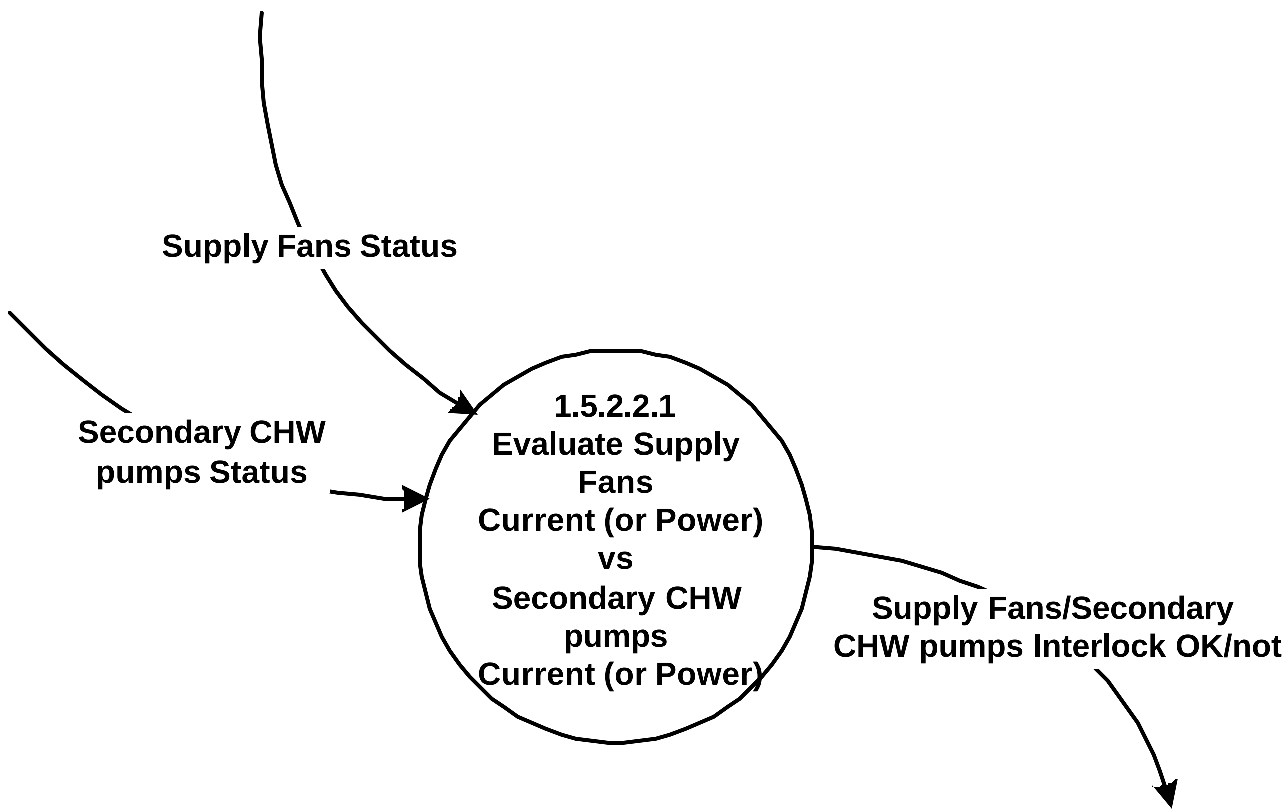
If the CHW Pumps Collective Status = "On" and the Supply Fan Status = "Off" for all of the air handlers served by this set of CHW Pumps, then set the Supply Fans/CHW Pumps Interlock OK/not for this CHW Pumps = "Not OK." These CHW Pumps is operating unnecessarily and is wasting energy. The CHW Pumps should not operate unless at least one of the supply fans in an air handler served by these CHW Pumps is on.

Notes: This diagnostic can be applied to current (or power) measured for each supply fan individually or to the collective current for all supply fans served by a CHW pump together.

Equipment status is determined in Process 7.0.

Ref. File: 5.8 supply fan-CHW pump interlock.doc

1.5.2.2 Verify Supply Fans/ Secondary Pumps Interlock



1.5.2.2.1 Evaluate Supply Fans Current (or Power) vs Secondary CHW pumps Current (or Power)

For chilled-water distirbution systems with secondary CHW pumps.

For each secondary set of CHW pumps,

compare the Secondary CHW pumps Collective Status and Supply Fans Status for the supply fans for each air handler served by this specific secondary CHW pump.

If the Secondary CHW pumps Collective Status = "On" and the Supply Fans Status = "On" for at least one of the air handlers served by this set of secondary CHW pumps, then set the Supply Fans/Secondary CHW Pumps Interlock OK/not for this set of secondary CHW pumps = "OK."

If the Secondary CHW pumps Collective Status = "Off" and the Supply Fans Status = "Off" for all of the air handlers served by this set of secondary CHW pumps, then set the Supply Fans/Secondary CHW Pumps Interlock OK/not for this set of secondary CHW pumps = "OK."

If the Secondary CHW pumps Collective Status = "Off" and the Supply Fans Status = "On" for at least one of the air handlers served by this set of Secondary CHW pumps, then set the Supply Fans/Seondary CHW Pumps Interlock OK/not for this set of secondary CHW pumps = "Possible problem with supply fan control--check to see if loads in the spaces served are being met" for supply fans with Supply Fans Status = "On" that are part of air handlers served by this set of secondary CHW Pumps.

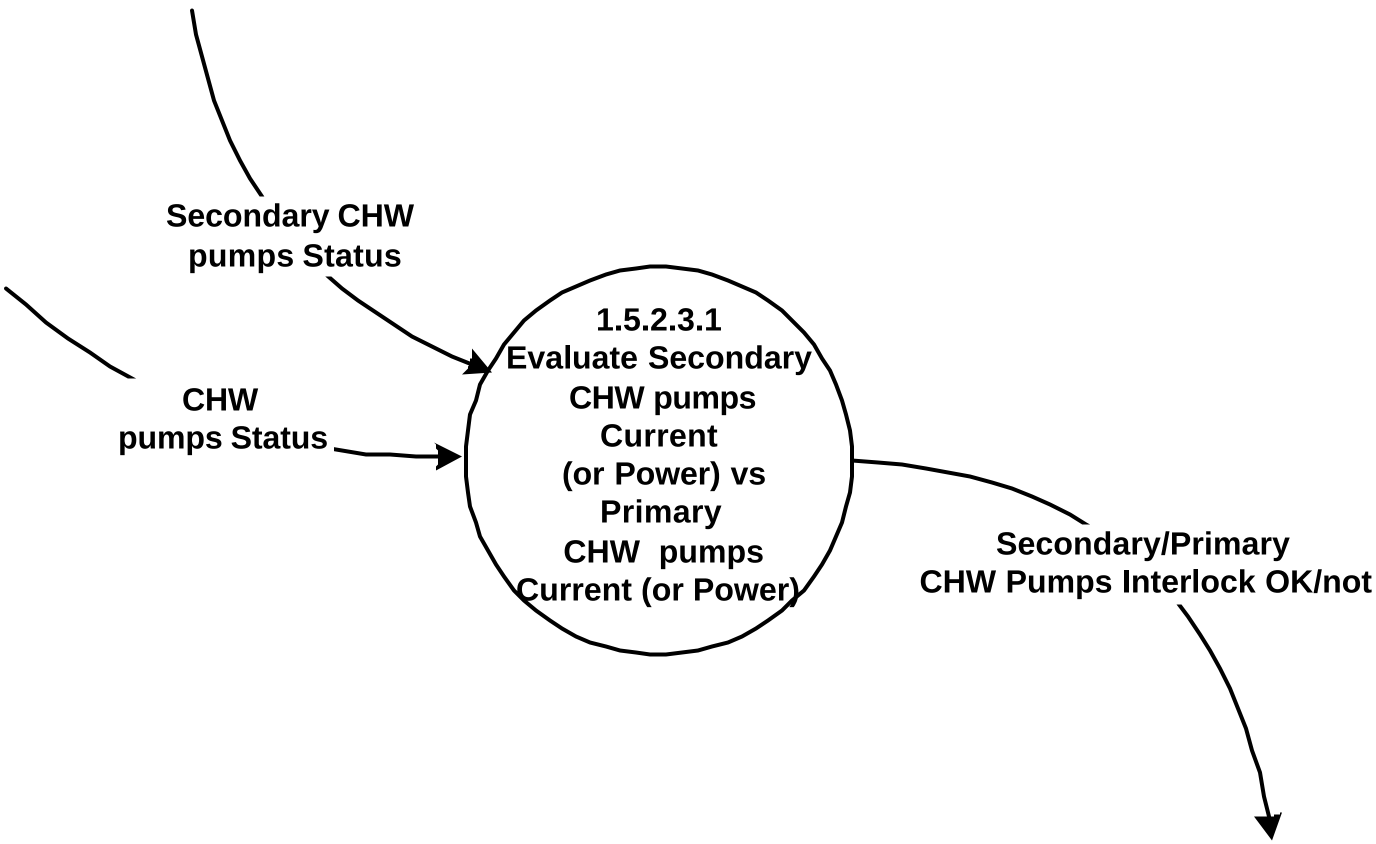
If the Secondary CHW pumps Collective Status = "On" and the Supply Fans Status = "Off" for all of the air handlers served by this set of Secondary CHW pumps, then set the Supply Fans/Secondary CHW Pumps interlock OK/not for this set of secondary CHW pump = "Not OK." This set of secondary CHW pumps is operating unnecessarily and is wasting energy. The set of secondary CHW pumps should not operate unless at least one of the supply fans in an air handler served by this set of secondary CHW pumps is on.

Notes: This diagnostic can be applied to current (or power) measured for each supply fan individually or to the collective current for all supply fans served by a set of secondary CHW pump togethers.

Equipment status is determined in Process 7.0.

Ref. File: 5.10 supply fan-2ndary CHW pump interlock.doc

1.5.2.3 Verify Secondary/Primary CHW Pumps Interlock



1.5.2.3.1 Evaluate Secondary CHW pumps Current (or Power) vs Primary CHW Pumps Current (or Power)

For each set of primary CHW pumps,

For each set of secondary CHW pumps served by the selected set of primary CHW Pumps,

Compare the primary CHW Pumps Collective Status and Secondary CHW pumps Collective Status for each set of secondary CHW pump served by this specific set of primary CHW Pumps.

If the primary CHW pumps Collective Status = "On" and the Secondary CHW pump Status = "On" for at least one of the secondary CHW pumps served by this set of primary CHW pumps, then set Secondary/Primary CHW Pumps Interlock OK/not for this set of primary CHW pump = "OK."

If the primary CHW pumps Collective Status = "Off" and the Secondary CHW pump Status = "Off" for all of the secondary CHW pumps served by this set of primary CHW pumps, then set Secondary/Primary CHW Pumps Interlock OK/not for this set of primary CHW pumps = "OK."

If the primary CHW pumps Collective Status = "Off" and the Secondary CHW pump Status = "On" for at least one of the secondary CHW pumps served by this set of primary CHW pumps, then set Secondary/Primary CHW Pumps Interlock OK/not for this set of primary CHW pumps = "Not OK." The secondary CHW pumps that are one are wasting energy. Secondary CHW pumps should only operate when the set of primary CHW pumps is operating.

If the primary CHW Pumps Collective Status = "On" and the Secondary CHW pump Status = "Off" for all of the secondary CHW pumps served by this set of primary CHW pumps, then set Secondary/Primary CHW Pumps Interlock OK/not for this set of primary CHW pumps = "Not OK." This set of primary CHW pumps is operating unnecessarily and is wasting energy. The set of primary CHW pump should not operate unless at least one of the secondary CHW pumps served by this set of primary CHW pumps is on.

Notes: This diagnostic can be applied to current (or power) measured for each secondary CHW pump individually or to the collective current for all secondary CHW pumps served by a CHW pump together.

Equipment status is determined in Process 7.0.

Ref. File: 5.9 secondary CHWP interlock.doc

1.6.0 Diagnose Chiller Performance

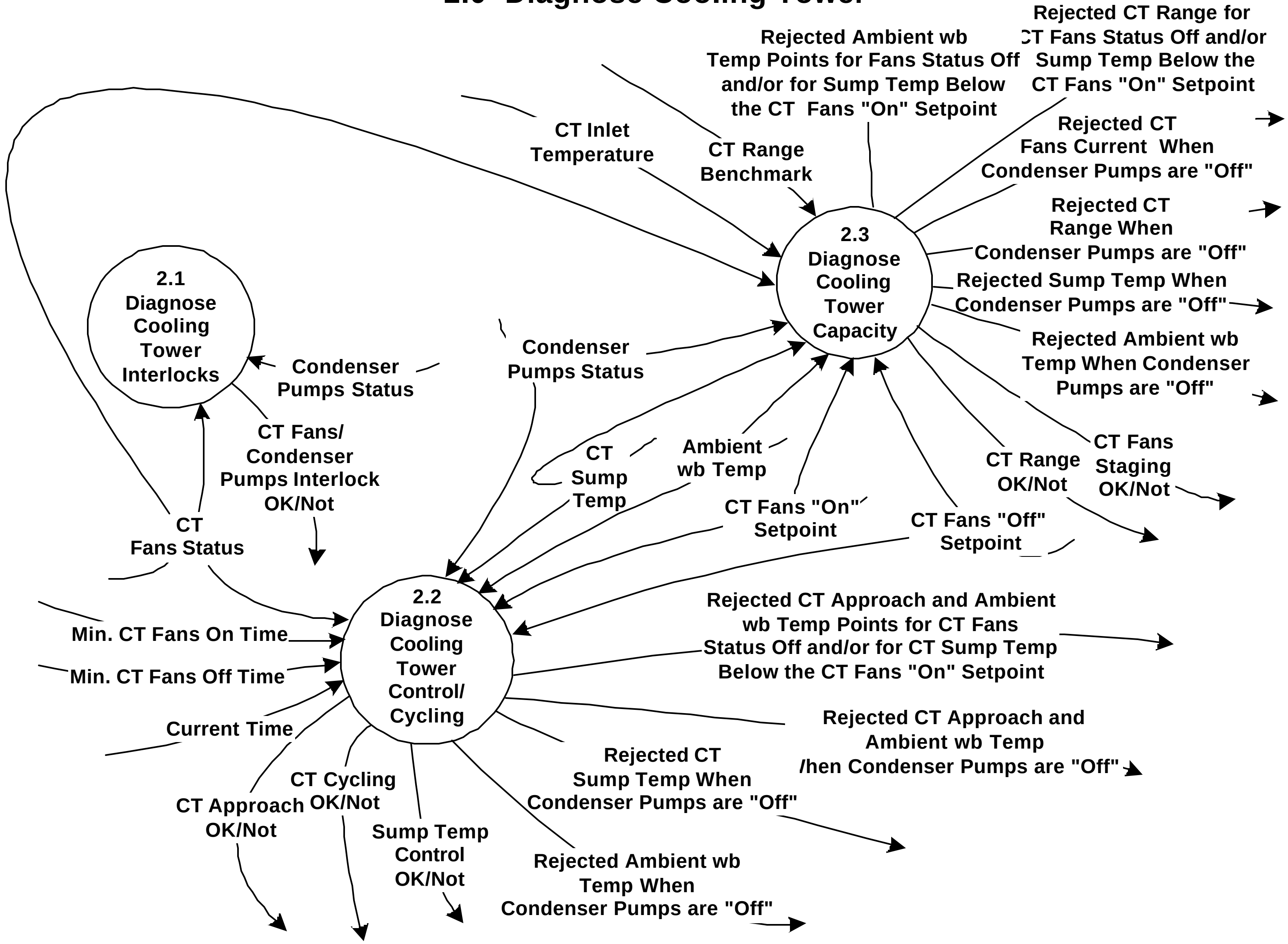
Placeholder only for Round 2.

Chiller Performance is a candidate for development of diagnostics for Round 2.

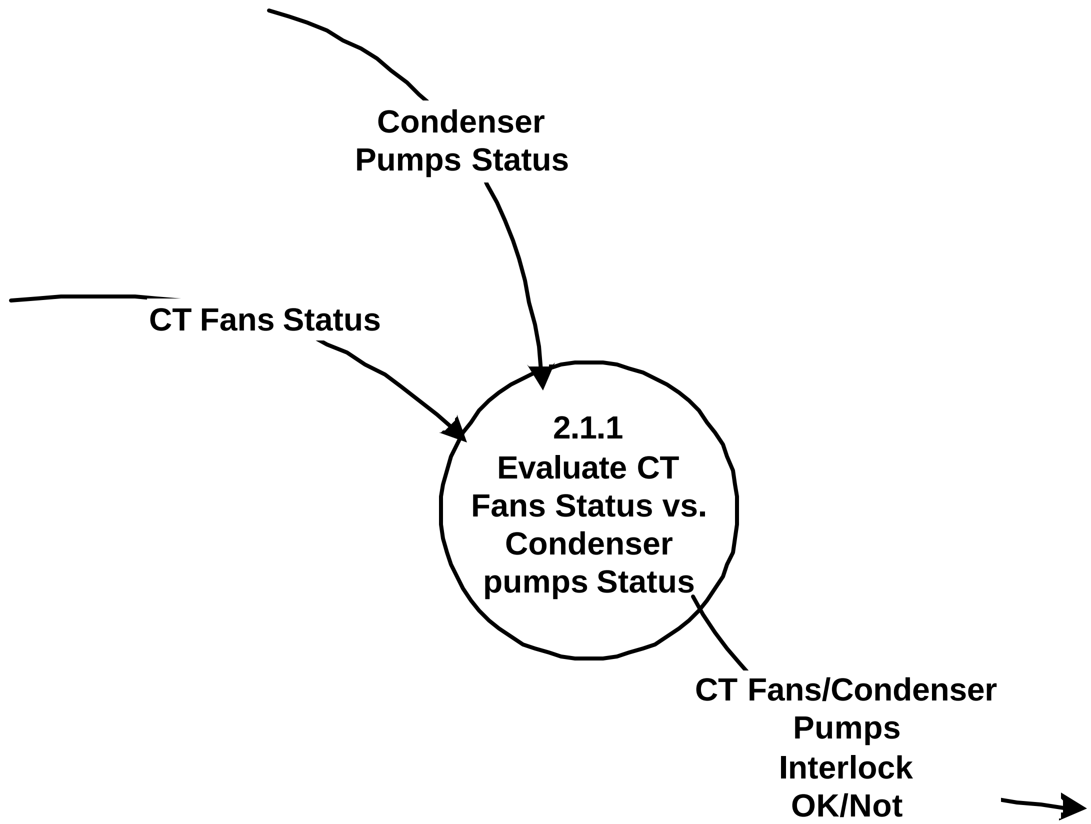
Enforma help suggests 4 plots that may be useful for Chiller Performance Diagnostics:

- ✓ Compressor Power vs. Ambient Temperature
- ✓ Compressor Power vs. Condenser Inlet Temperature (cooling tower outlet temperature)
- ✓ Compressor Power vs. Chiller Delta T
- ✓ Compressor Power vs. Chiller Inelt Temperature

2.0 Diagnose Cooling Tower



2.1 Diagnose Cooling Tower Interlocks



2.1.1 Evaluate CT Fans Status vs. Condenser Pumps Status

Compare the CT Fans Status and Condenser Pumps Status for the current time.

If the CT Fans Status = "On" and the Condenser Pumps Status = "On," then CT Fans/Condenser Pumps Interlock OK/Not = "OK"

If the CT Fans Status = "Off" and the Condenser Pumps Status = "Off," then CT Fans/Condenser Pumps Interlock OK/Not = "OK."

If the CT Fans Status = "On" and the Condenser Pumps Status = "Off," then CT Fans/Condenser Pumps Interlock OK/Not = "Not OK." The CT Fans must be off when the condenser pumps are off, otherwise energy is being wasted.

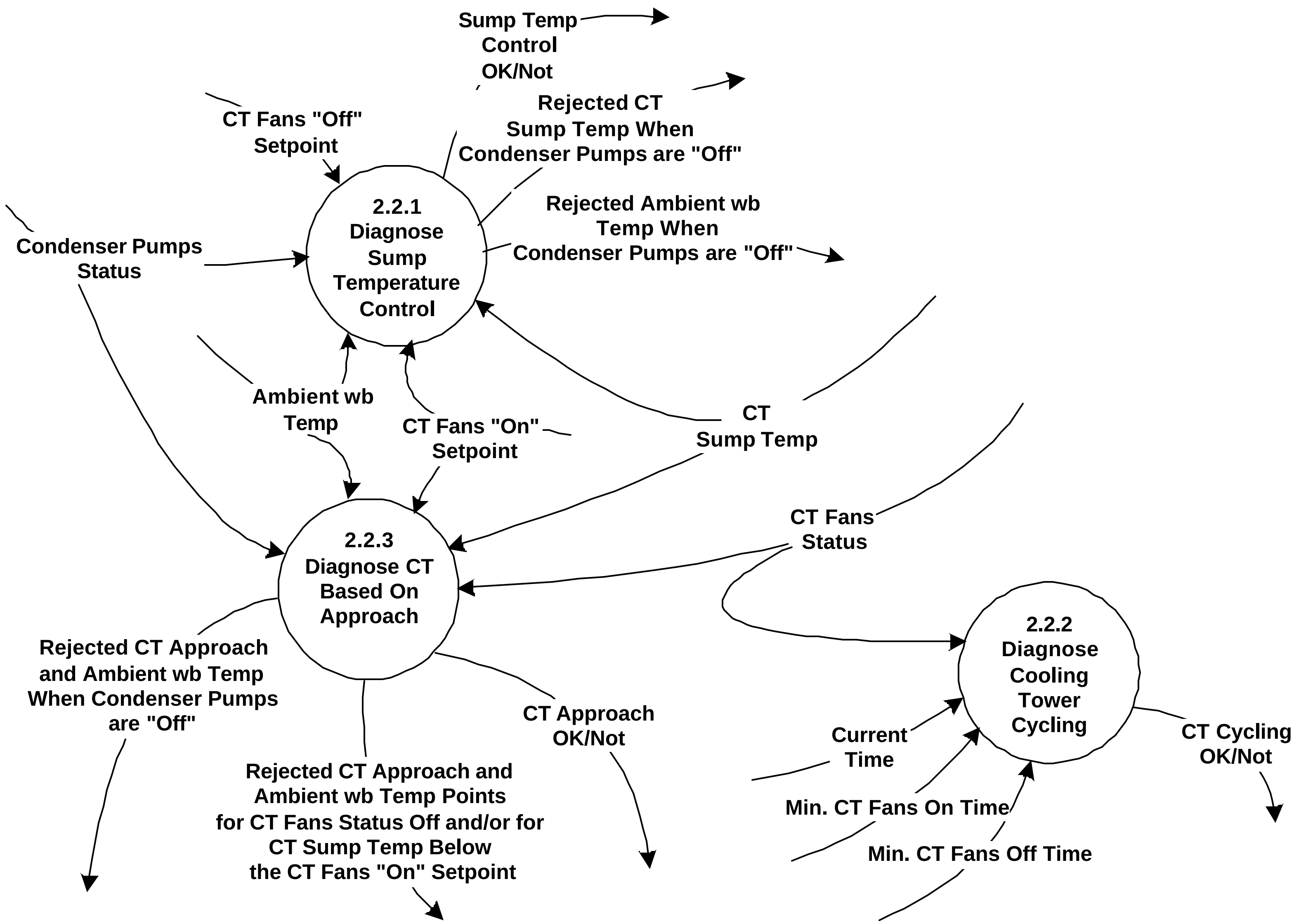
If the CT Fans Status = "Off" and the Condenser Pumps Status = "On," then CT Fans/Condenser Pumps Interlock OK/Not = "OK." The cooling tower Fans may be off when the condenser pumps are running, but this should not always be the case.

Note: This process uses as inputs the CT Fans Status and the Condenser Pumps Status that are determined in Process 7.0.

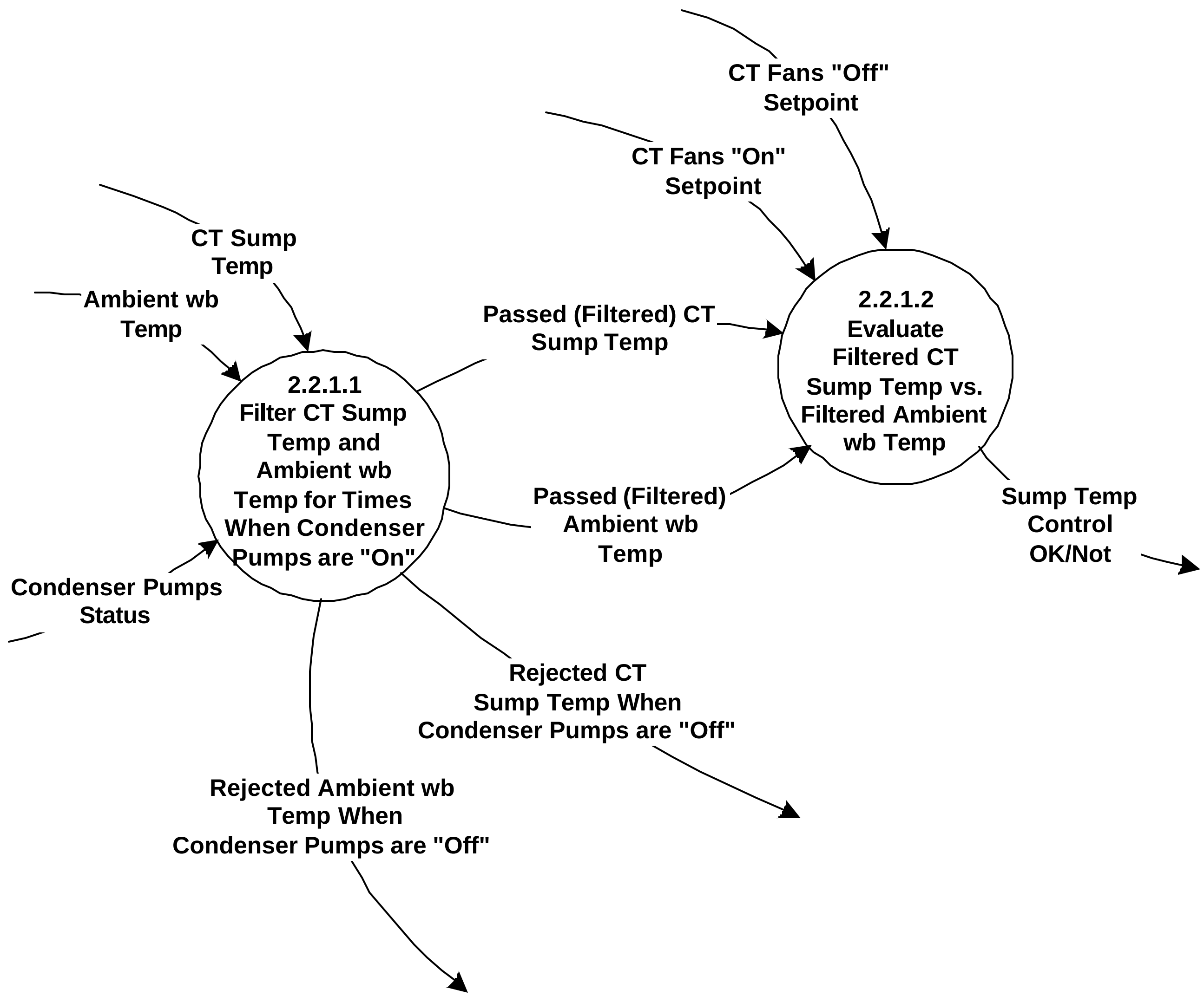
Values of CT Fans/Condenser Pumps Interlock OK/Not = "OK" should be interpretted more precisely as "no problem has been detected with this interlock." It is possible that no problem is detected under current conditions,yet an interlock problem exists. This is particularly true when CT Fans Status = "Off" and Condenser Pumps Status = "On," which while OK under some condtions is not always OK. Additional diagnostics would be useful here.

Ref. File: 1.22 Evaluate Plot of CT Fan vs. CCP

2.2 Diagnose Cooling Tower Temperature Control/Cycling



2.2.1 Diagnose Sump Temperature Control



2.2.1.1 Filter CT Sump Temp and Ambient wb Temp for Times When Condenser Pumps are On

For each triplet of (Condenser Pumps Status, CT Sump Temperature, and Ambient wb Temperature)

reject (i.e., filter out) those triplets for which Condenser Pumps Status = off.
pass those triplets for which Condenser Pumps status = on.

2.2.1.2 Evaluate Filtered CT Sump Temp vs. Filtered Ambient wb Temp

Determine if CT fans are on when Sump Temp is above its on setpoint

If Sump Temperature > CT Fans On Setpoint and CT Fans Status = "On,"
then set Sump Temp Control OK/Not= "OK"

If Sump Temperature > CT Fans On Setpoint and CT Fans Status = "Off,"
then set Sump Temp Control OK/Not= "Not OK. The CT fans are off but should be on."

Possible causes include:

- control problem
- sump temperature sensor problem
- electrical problem (motor failure)
- other problems with the fan motor

Determine if CT fans are off when sump Temp is below the off setpoint

If Sump Temperature <= CT Fans Off Setpoint and CT Fans Status = "On,"
then set Sump Temp Control OK/Not= "Not OK. The CT fans are on but should be off."

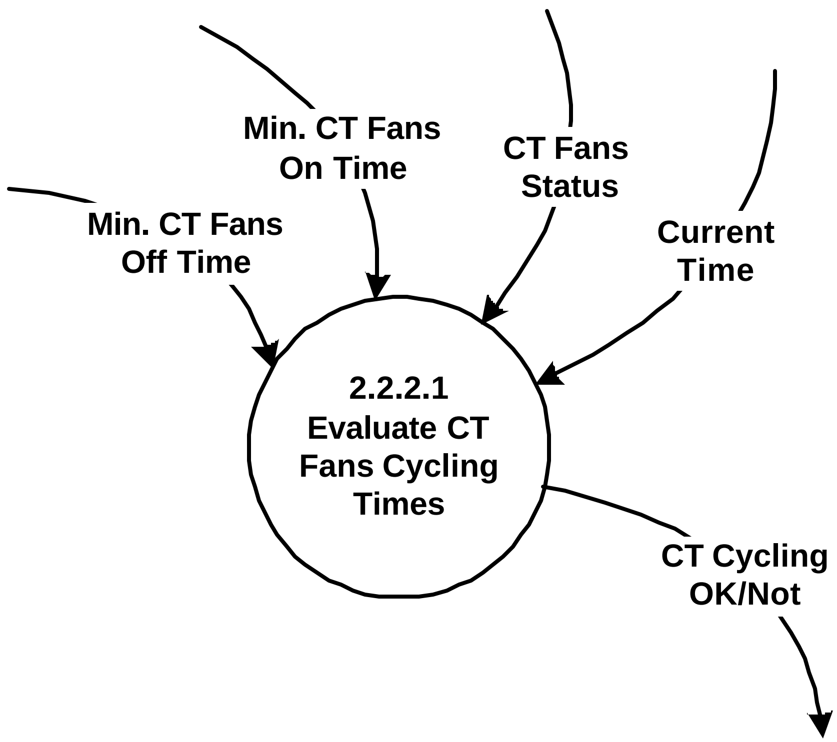
Possible causes include:

- control problem
- actuator or relay problem

If Sump Temperature <= CT Fans Off Setpoint and CT Fans Status = "Off,"
then set Sump Temp Control OK/Not= "OK."

Ref. File: 2.1.1 Sump Temperature Control Diagnostics

2.2.2 Diagnose Cooling Tower Cycling



2.2.2.1 Evaluate CT Fans Cycling Times

Determine if new cycling information is available to analyze (fans currently on).
If CT Fans Status = "On" and Last CT Fans Status = "On," then terminate this evaluation. There is nothing new to check.

If CT Fans Status = "On" and Last CT Fans Status = "Off," then set Last CT Fans On Time = Current Time and check Last CT Fans Off Interval.

If Last CT Fans Off Interval >= Minimum CT Fans Off Time, then CT Cycling OK/Not = "OK."

If Last CT Fans Off Interval < Minimum CT Fans Off Time, then CT Cycling OK/Not = "Not OK." The CT fans are not staying off long enough during cycling.

Possible causes include::

The timer that is supposed to eliminate short cycling is not working properly.
The "on" and "off" control setpoints for the fans are too close to one another.

Possible corrective actions include:

Check the control algorithm for the fans if it is controlled by software. Increase the minimum off time in the software, as necessary, to meet the manufacturers specification for minimum off time.
Check the performance of the time-delay relay. Energize the relay and manually time the delay until action. Compare the measured time with the specification. Replace or adjust the relay if it is out of spec.

Determine if new cycling information is available to analyze (fans currently off).
If CT Fans Status = "Off" and Last CT Fans Status = "Off," then terminate this evaluation. There is nothing new to check.

If CT Fans Status = "Off" and the Last CT Fans Status = "On," then set Last CT Fans Off Time = Current Time and check Last Fan On Interval.

If Last CT Fans On Interval >= Minimum CT Fans On Time, then CT Cycling OK/Not = "OK."

If Last CT Fans On Interval < Minimum CT Fans On Time, then CT Cycling OK/Not = "Not OK." The CT fans are not staying on long enough during cycling.

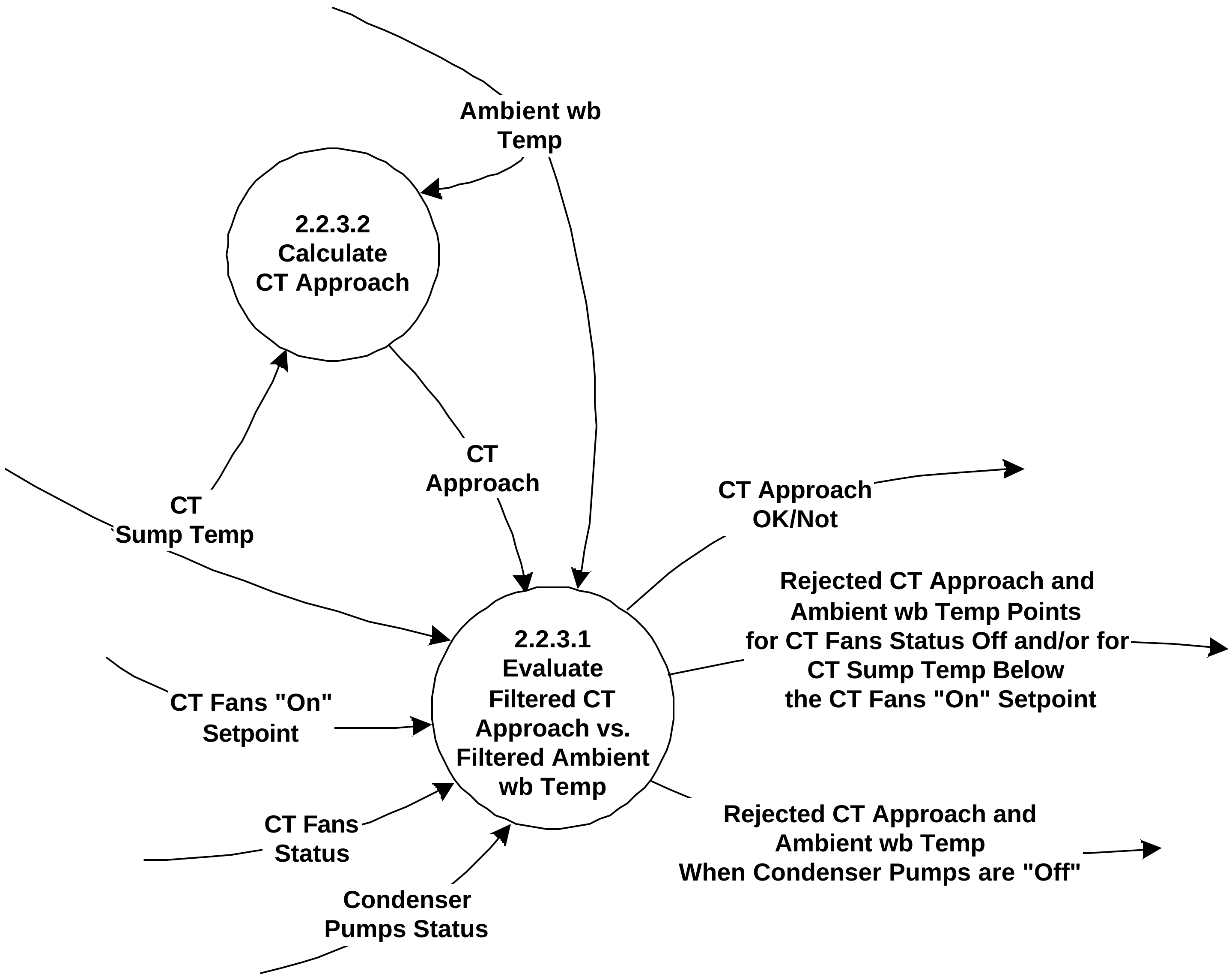
Possible causes include:

The timer that is supposed to eliminate short cycling is not working properly.
The "on" and "off" control setpoints for the fans are too close to one another.
The cooling tower capacity is too great for the load, so the fans rapidly cycle off (i.e., the on time is very short) because the load is met quickly.

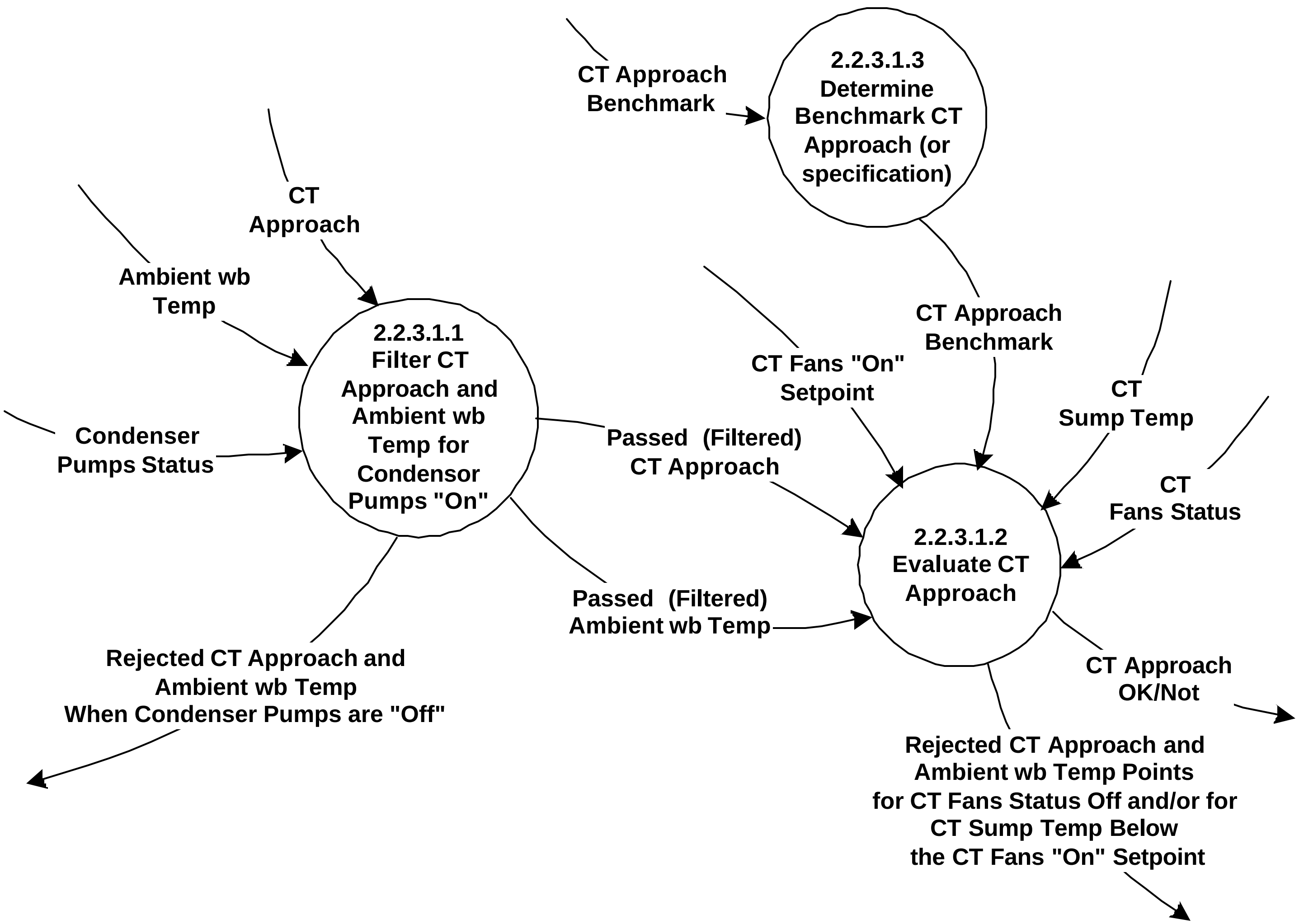
Possible corrective actions include:

Check the control algorithm for the fans if it is controlled by software. Increase the minimum off time in the software, as necessary, to meet the manufacturers specification for minimum off time.
Check the performance of the time-delay relay. Energize the relay and manually time the delay until action. Compare the measured time with the specification. Replace or adjust the relay if it is out of spec.

2.2.3 Diagnose CT Based on Approach



2.2.3.1 Evaluate Filtered CT Approach vs. Filtered Ambient wb Temp

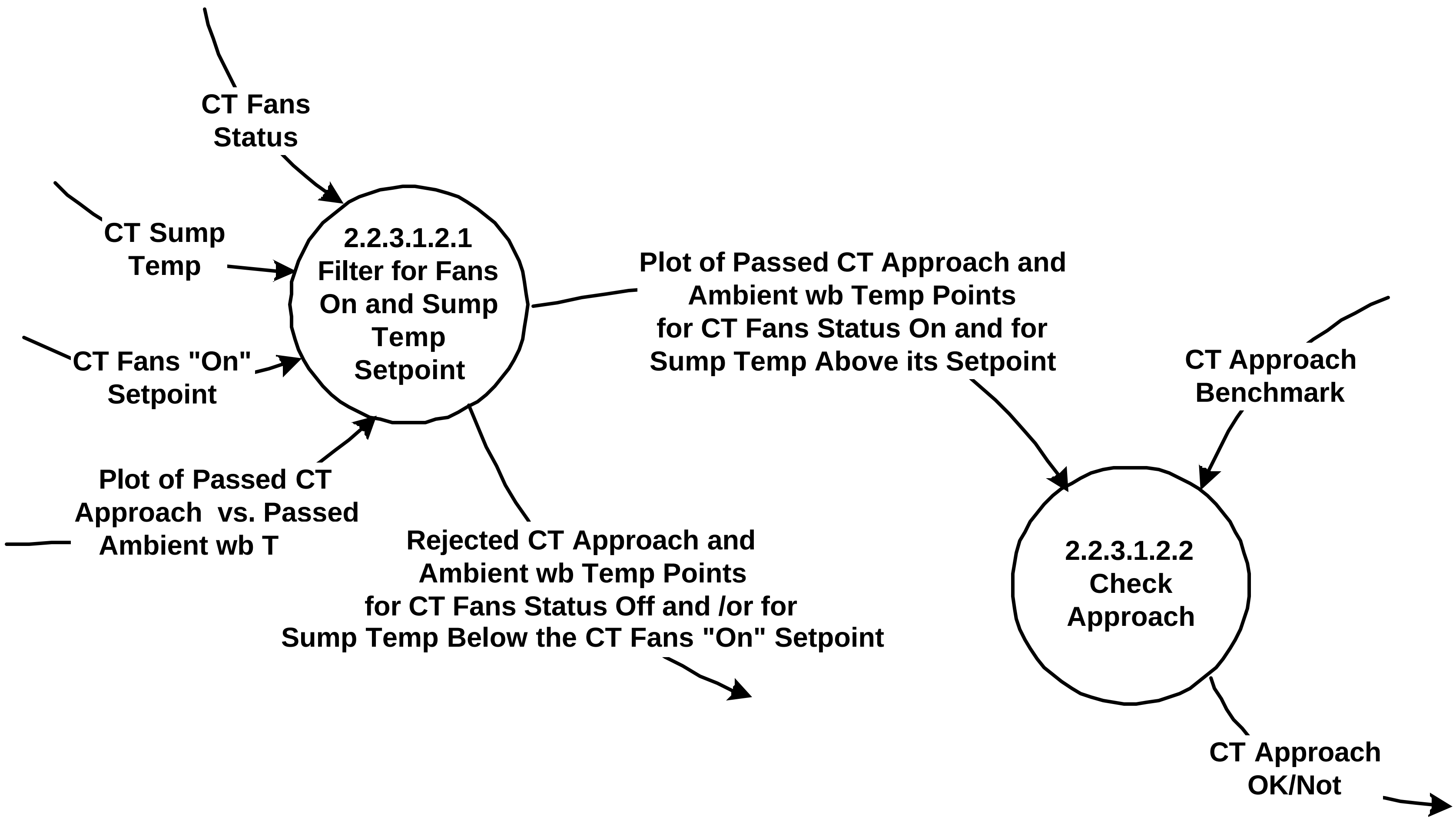


2.2.3.1.1 Filter CT Approach and Ambient wb Temp for Condensor Pumps "On"

For each triplet of (Condenser Pumps Status, CT Approach, and Ambient wb Temperature)

reject (i.e., filter out) those triplets for which Condenser Pumps Status = off.
pass those triplets for which Condenser Pumps Status = on.

2.2.3.1.2 Evaluate CT Approach Behavior



2.2.3.1.2.1 Filter for Fans "On" and Sump Temp Setpoint

For each point on the Plot of filtered CT Approach vs. Filtered Ambient wb Temp, reject it

if the CT Fans Status is "off" or
if the Sump Temperature < CT Fans "on" setpoint

otherwise, accept it (pass it).

Ref: 2.4 approach diagnostics discussion.doc

2.2.3.1.2.2 Check Approach

Compare values of CT Approach to the CT Approach Benchmark.

If CT Approach is <= CT Approach Benchmark, then set CT Approach OK/Not = "OK"

If CT Approach is > CT Approach Benchmark, then there is a problem (not OK) with CT heat rejection. Set CT Approach OK/Not = "Not OK. There is a problem with heat rejection from the cooling tower."

Possible causes of heat rejection degradation (i.e., CT Approach OK/Not = Not OK):

Cooling tower media fouled due to mineral deposits or ambient dirt/dust/etc. Need to inpsect.

Restricted airflow for other reasons (e.g., piece of cardboard stuck over part of cooling tower air inlet)

Condenser pump fouling, pipe fouling, or other restrictions on the water side.

Ref. File: 2.4 Approach diagnostics discussion.doc

2.2.3.1.3 Determine Benchmark CT Approach

CT Approach Benchmark is a user input (in the current process; see note below).

2.2.3.2 Calculate CT Approach

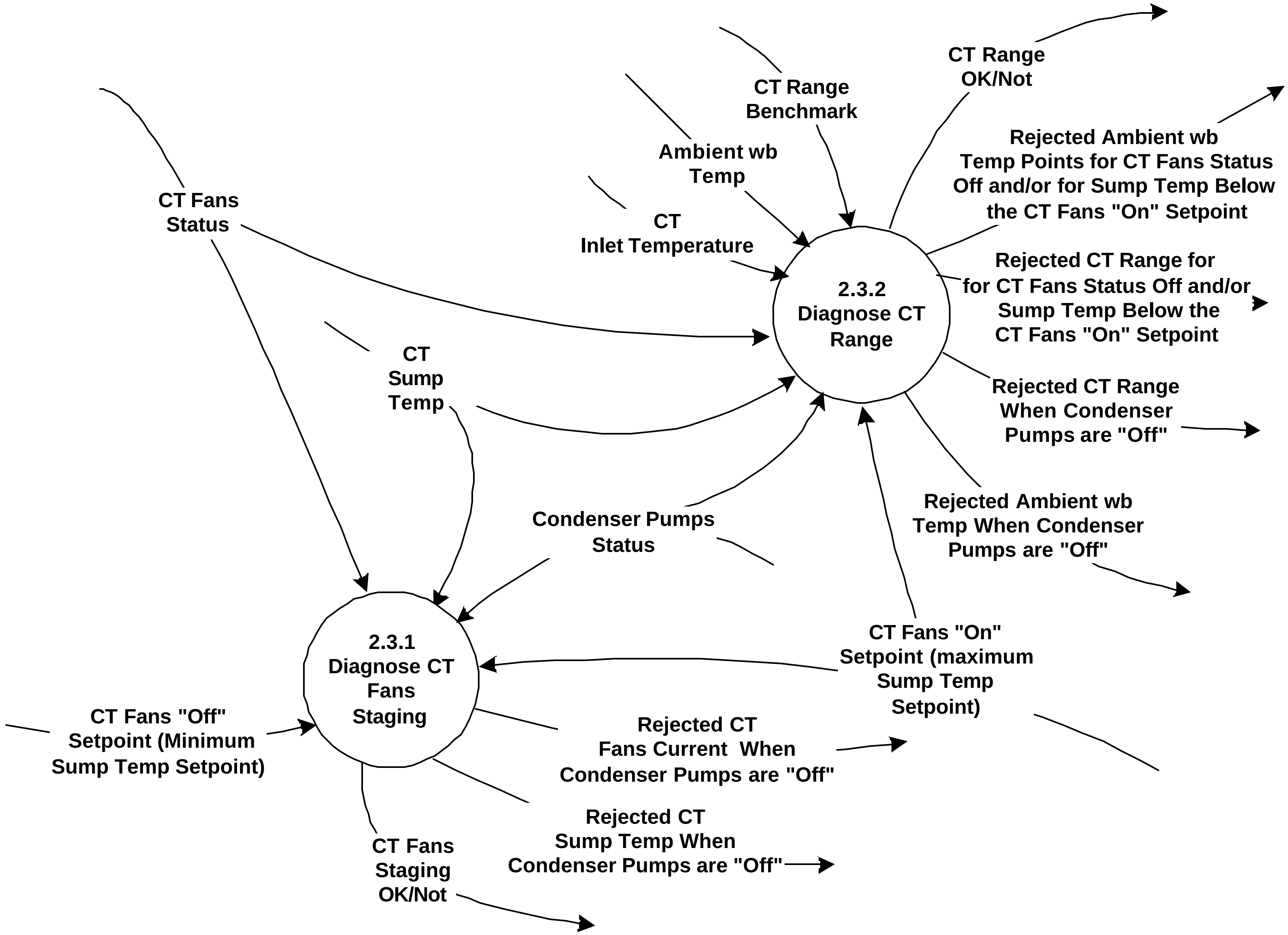
For each pair of values of Sump Temperature and Ambient wb Temperature corresponding to the same time, calculate the CT Approach using

CT Approach = Sump Temp - Ambient Wet Bulb Temp

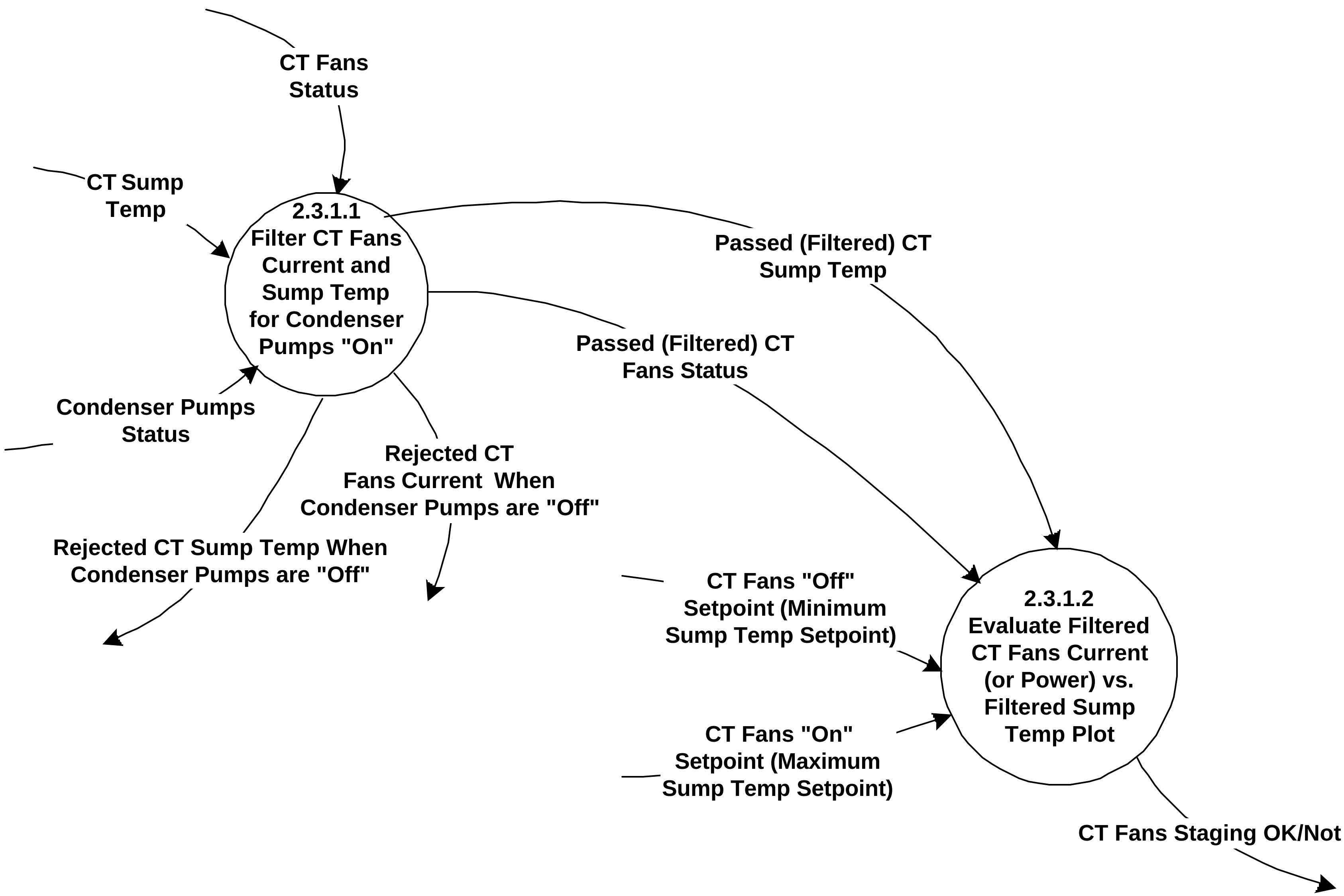
Note: Approach is not "controlled" - it is the difference between the sump temperature, which IS controlled, and the ambient wb temperature, which is NOT controlled.

Ref: 2.4 approach diagnostics.doc

2.3 Diagnose Cooling Tower Capacity



2.3.1 Diagnose CT Fans Staging



2.3.1.1 Filter CT Fans Current and Sump Temp for CT Pumps "On"

For each triplet of (Condenser Pumps Status, CT Fans Status, and CT Sump Temperature)

reject (i.e., filter out) those triplets for which Condenser Pumps Status = off.

pass those triplets for which Condenser Pumps status = on.

2.3.1.2 Evaluate Filtered CT Fans Current (or Power) vs. Filtered Sump Temp Plot

Compare Sump Temperature to the CT Fans "On" Setpoint (maximum Sump Temperature Setpoint).

If Tsump < CT Fans "On" Setpoint, then set Fans Staging OK/Not = "OK (as far as we can tell)"

If Tsump > CT Fans "On" Setpoint, and CT Fans Status = "On" for all CT fans, then set Fans Staging OK/Not = "OK."

If Tsump > CT Fans "On" Setpoint and CT Fans Status [1] "On" for all CT fans (i.e., all CT fans are not on), set Fans Staging OK/Not = "not OK. There is a fan staging problem and the cooling tower is not maintaining the Sump Temp as low as it could/should."

Compare Tsump to the CT Fans "Off" Setpoint (minimum Sump Temperature Setpoint).

If Tsump > CT Fans "Off" Setpoint, then set Fans Staging OK/Not = "OK (as far as we can tell)."

If Tsump < CT Fans "Off" Setpoint, and if CT Fans Status = "Off" for all CT Fans (i.e., all CT fans are off), then set Fans Staging OK/Not = "OK."

If Tsump < CT Fans "Off" Setpoint, and If any CT Fans Status = "On" (i.e., any CT fan is "on"), then set Fans Staging OK/Not = "Not OK. There is a fan staging problem and energy is being wasted. All CT Fans should be off."

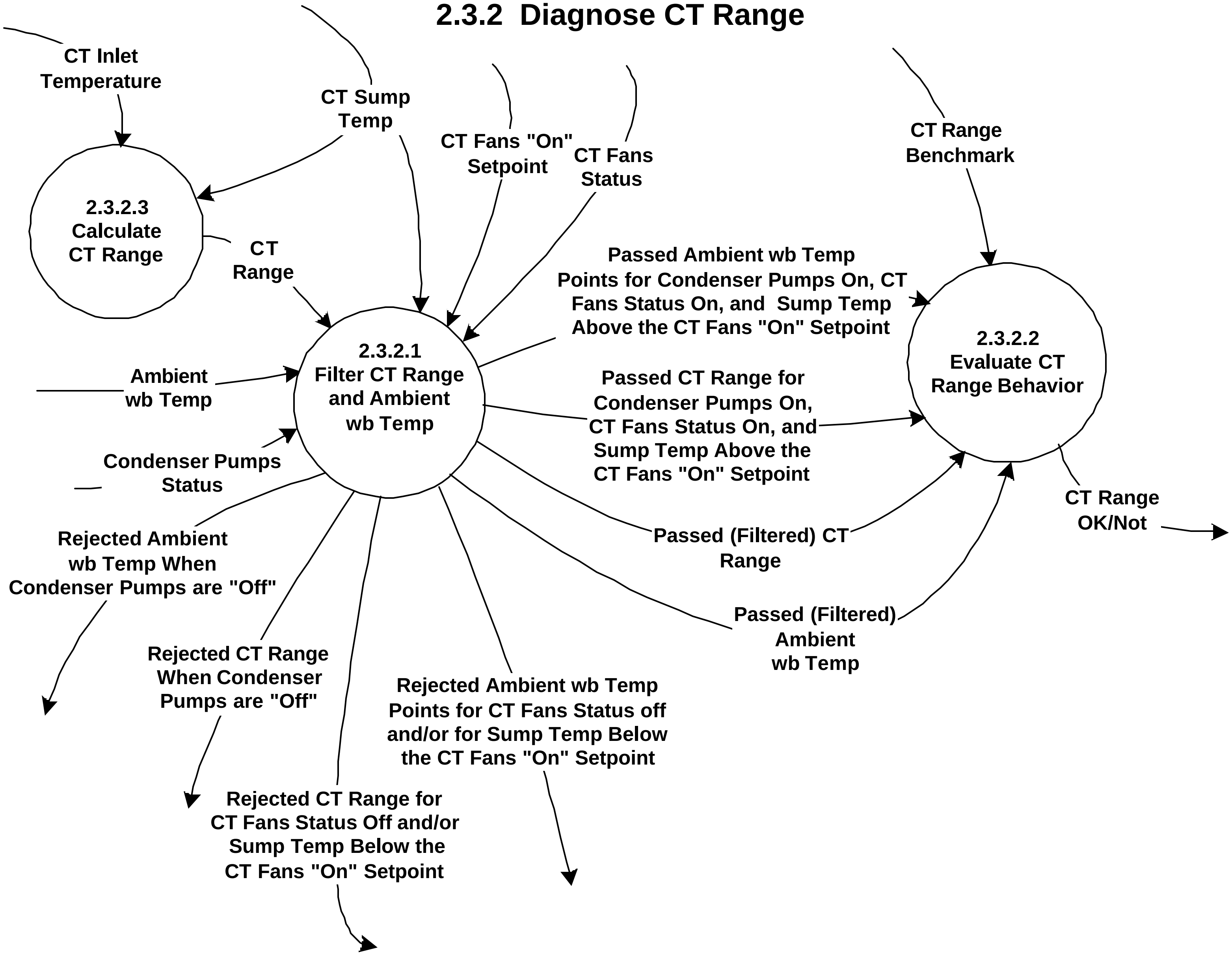
Note:
The minimum and maximum sump temp setpoints are currently specified as inputs. A procedure could be developed to derive them from performance data. This would reduce the number of user inputs required.

Note: A process for checking the individual fan stages has not been specified here. it would need to be added. See Behavior 3 in the reference file.

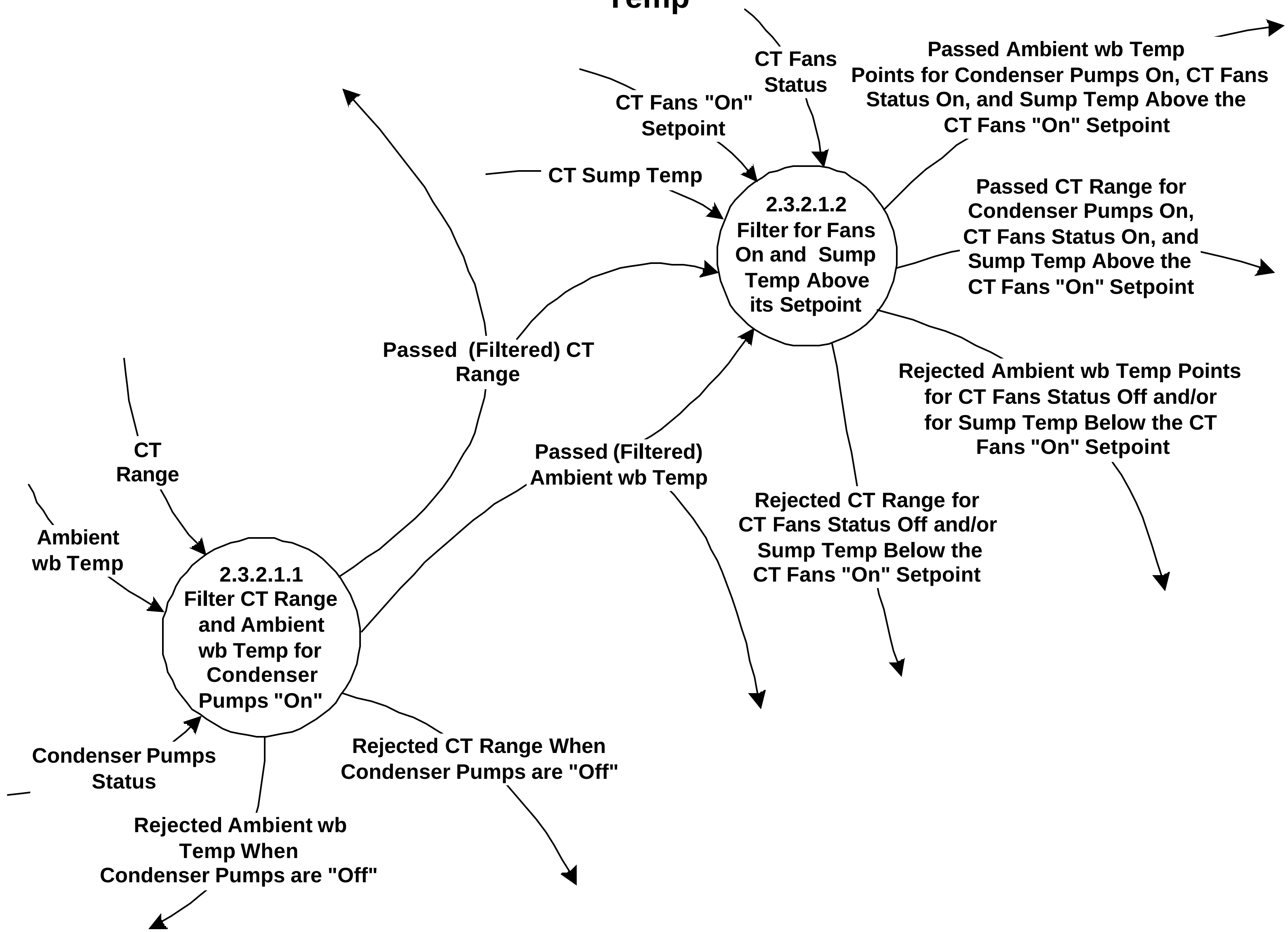
Tsump = Sump Temp
Tsump maximum setpoint = maximum Sump Temperature setpoint
Tsump minimum setpoint = minimum Sump Temperature setpoint

Ref. File: 3.3 fan staging diagnostic.doc

2.3.2 Diagnose CT Range



2.3.2.1 Filter CT Range and Ambient wb Temp



2.3.2.1.1 Filter CT Range and Ambient wb Temp for Condenser Pumps "On"

For each triplet of (Condenser Pumps Status, CT Range, and Ambient wb Temperature)

reject (i.e., filter out) those triplets for which Condenser Pumps Status = off.

pass those triplets for which Condenser Pumps status = on.

2.3.2.1.2 Filter for Fans "On" and Sump-Temp Setpoint

For each point on the Plot of filtered CT Range vs. Filtered Ambient wb Temp, reject it

if the Fans Status is "off" or

if the Sump Temperature is below the CT Fans "On" Setpoint (Maximum Sump Temperature Setpoint).

otherwise, accept it (pass it).

2.3.2.2 Evaluate CT Range Behavior

Compare values of CT Range to the Range Benchmark..

If CT Range is >= Range Benchmark, then set CT Range OK/Not= "OK"

If CT Range is < Range Benchmeark, then set CT Range OK/Not = "Not OK. There is a problem with CT heat rejection and it is performing at less than expected capacity."

Possible heat rejection degradation causes:

Tower media fouling due to mineral deposits or ambient dirt/dust/etc.

Restricted airflow

Condenser pump fouling, again, pipe fouling, restrictions

Tower to small for load (design problem)

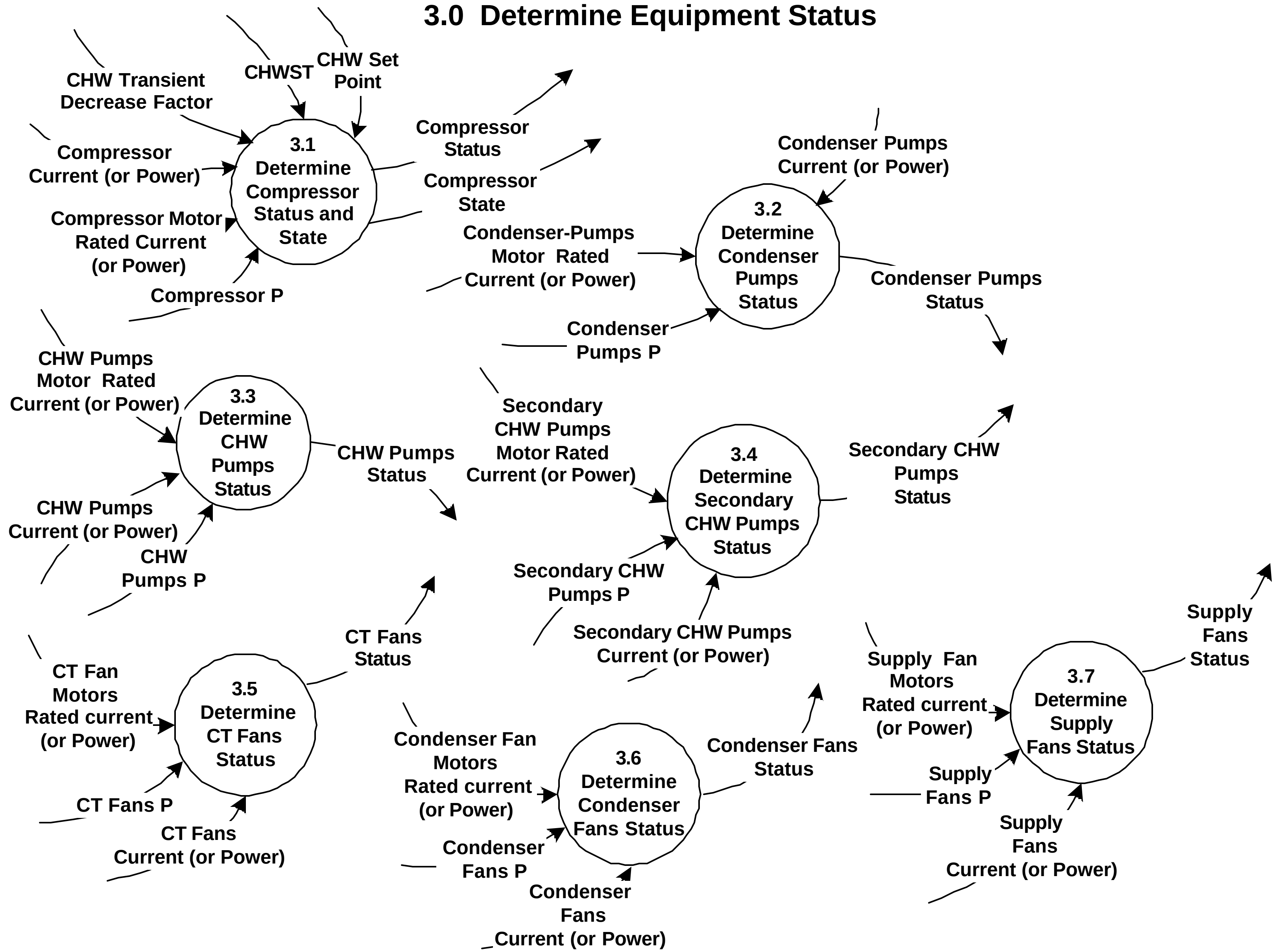
Ref. File: 3.2.3 Range diagnostics discussion.doc

2.3.2.3 Calculate CT Range

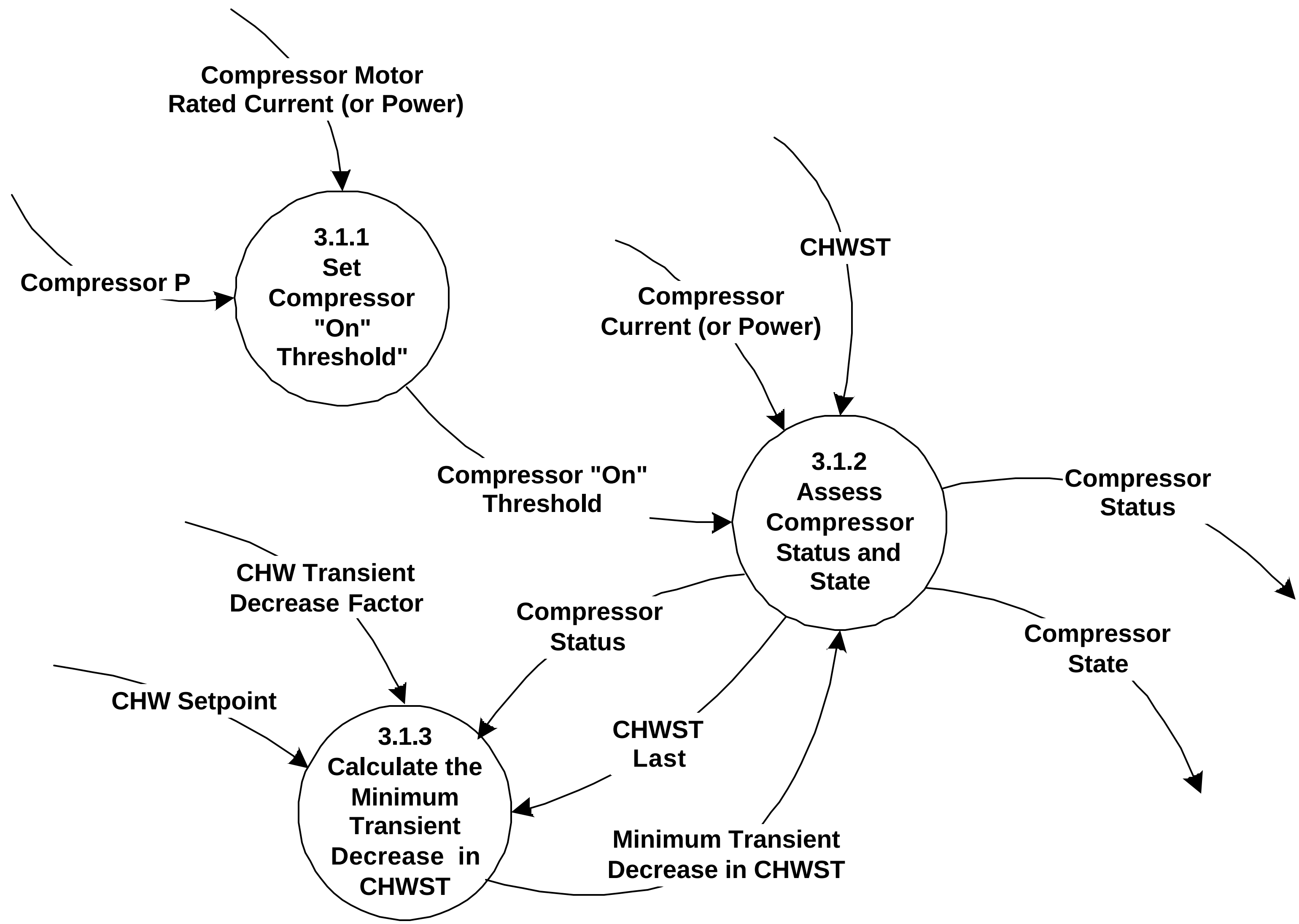
For each time increment (and pair of necessary temperature values), calculate the CT Range, using the formula

CT Range = CT Sump Temperature - CT Inlet Temperature.

3.0 Determine Equipment Status



3.1 Determine Compressor Status and State



3.1.1 Set Compressor "On" Threshold

Calculate the Compressor "On" Threshold using

Compressor "On" Threshold = Compressor P x Compressor Motor Rated Current (or Power)

Notes:

The chiller is "on" when the compressor is "on;" therefore, the chiller status can be determined by evaluating the compressor on/off status. As the result, the Chiller "On" Threshold is set by setting the Compressor "On" threshold.

The Compressor "On" Threshold is calculated from input power rating of the compressor motor.

Compressor P has values that range from 10 to 50% -- this can be a user input.

Ref file: 2.1CHW temperature control.doc

3.1.2 Assess Compressor Status and State

For each value of Compressor Current (or Power),
    compare Compressor Current (or Power) to the Compressor "On" Threshold.
        If the value of Compressor Current (or Power) <= Compressor "On" Threshold, then set Compressor Status = "Off" and set Compressor State = "Off"
        If the value of Compressor Current (or Power) > Compressor "On" Threshold, then set Compressor Status = "on."

    If Compressor Status = "On", then evaluate Compressor State as follows:
        Update the value of Last Compressor State, using

            Last Compressor State = Compressor State.

        Determine and assign the new value of Compressor State for the current time
            Check if the compressor is already in steady state
                If Last Compressor State = Steady,
                then set Compressor State = "Steady"

            If Compressor Status = "On" and the Last Compressor State = "Transient", then
            Calculate Drop in CHW Supply Temperature using

                Drop in CHWST = CHWST Last - CHWST

            Compare Drop in CHW Supply Temperature to the Minimum Transient Decrease in CHWST.
                If Drop in CHWST > Minimum Transient Decrease in CHWST, then set Compressor State = "Transient".

                If Drop in CHWST <= Minimum Transient Decrease in CHWST, then set Compressor State = "Steady"

Update CHWST Last
    CHWST Last = CHWST

Note: Compressor Status = Chiller Status

3.1.3 Calculate the Minimum Transient Decrease in CHWST

Calculate the Minimum Transient Decrease in CHWST using the relation:

Minimum Transient Decrease in CHWST = CHW Transient Decrease Factor * (CHWST at Last Time Off - CHWST Setpoint)

Set new value of CHWST at Last Time Off,

If Compressor Status = "Off" and Last Compressor Status = "Off", then
set CHWST at Last Time Off = CHWST

If Compressor Status = "On" and Last Compressor Status = "Off", then
set CHWST at Last Time Off = CHWST Last

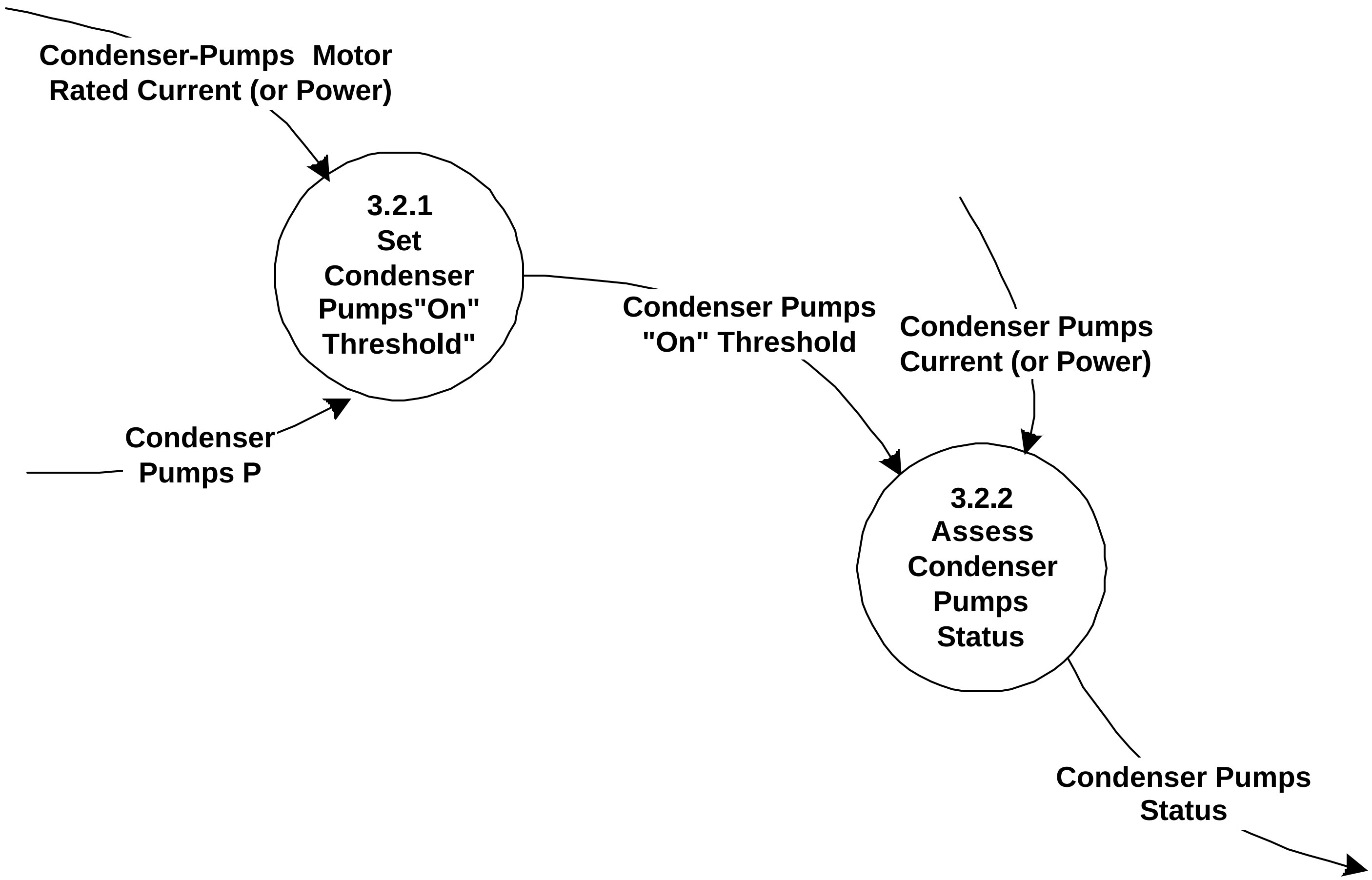
If Compressor Status = "On" and Last Compressor Status = "On" then
set CHWST at Last Time Off = CHWST at Last Off Time (i.e., not change).

Update Last Compressor Status

Last Compressor Status = Compressor Status*

*This over-writes the previous compressor status with the current status and should not be performed if the previous status is required in subsequent processing.

3.2 Determine Condenser Pumps Status



3.2.1 Set Condenser Pumps"On" Threshold"

Calculate the Condenser Pumps "On" Threshold using

Condenser Pumps "On" Threshold = Condenser Pumps P x Condenser Pump Motors Rated Current (or Power)

Notes:

Condenser Pumps P has values that range from 10 to 50% -- this can be a user input.

3.2.2 Assess Condenser Pumps Status

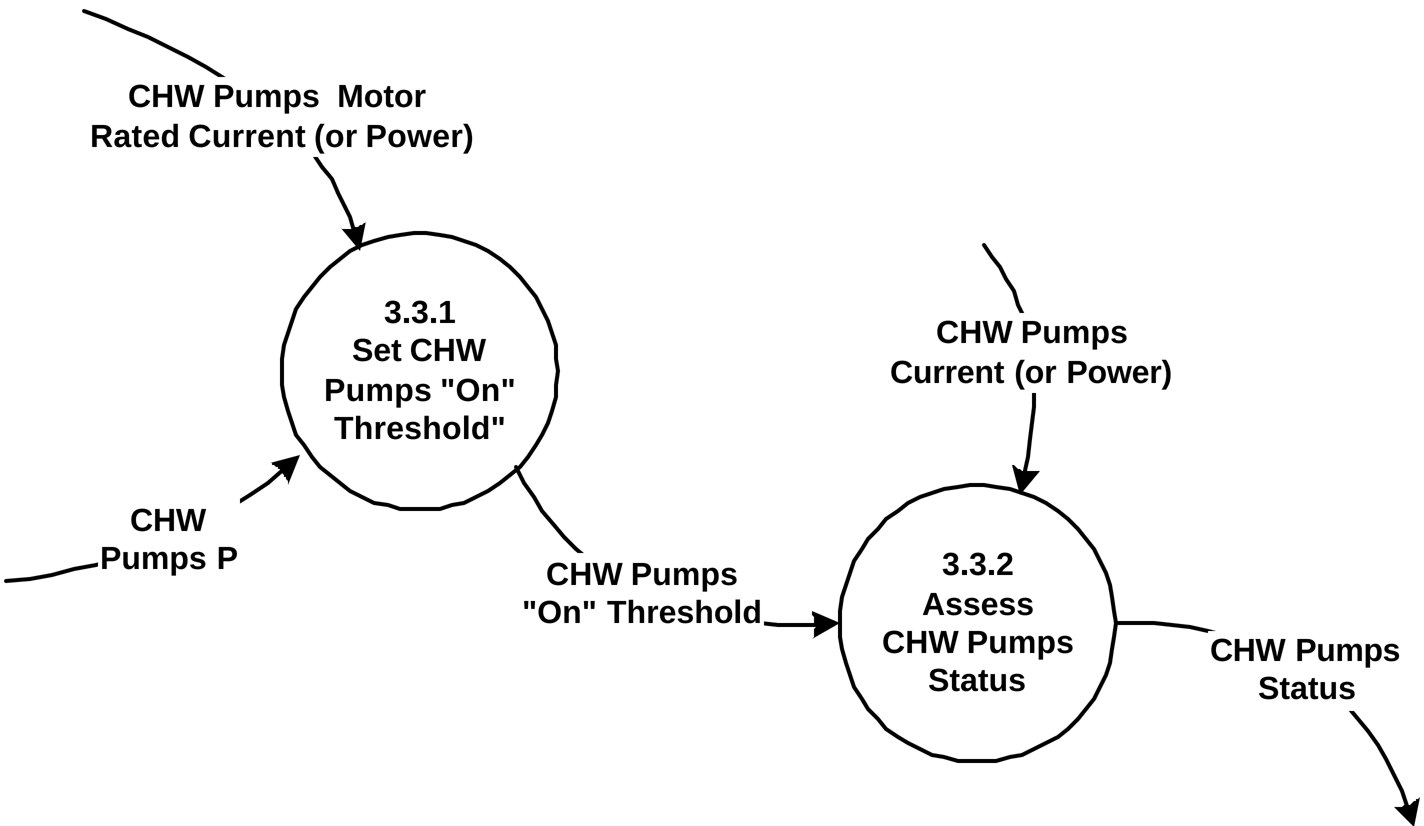
For each value of Condenser Pumps Current (or Power),

compare Condenser Pumps Current (or Power) to the Condenser Pumps "On" Threshold.

If the value of Condenser Pumps Current (or Power) <= Condenser Pumps "On" Threshold, then set Condenser Pumps Status = "Off."

If the value of Condenser Pumps Current (or Power) > Condenser Pumps "On" Threshold, then set Condenser Pumps Status = "On."

3.3 Determine CHW Pumps Status



3.3.1 Set CHW Pumps "On" Threshold

Calculate the CHW Pumps "On" Threshold using

CHW Pumps "On" Threshold = CHW Pumps P x CHW Pumps Motor Rated Current (or Power)

Notes:

CHW Pumps P has values that range from 10 to 50% -- this can be a user input.

3.3.2 Assess CHW Pumps Status

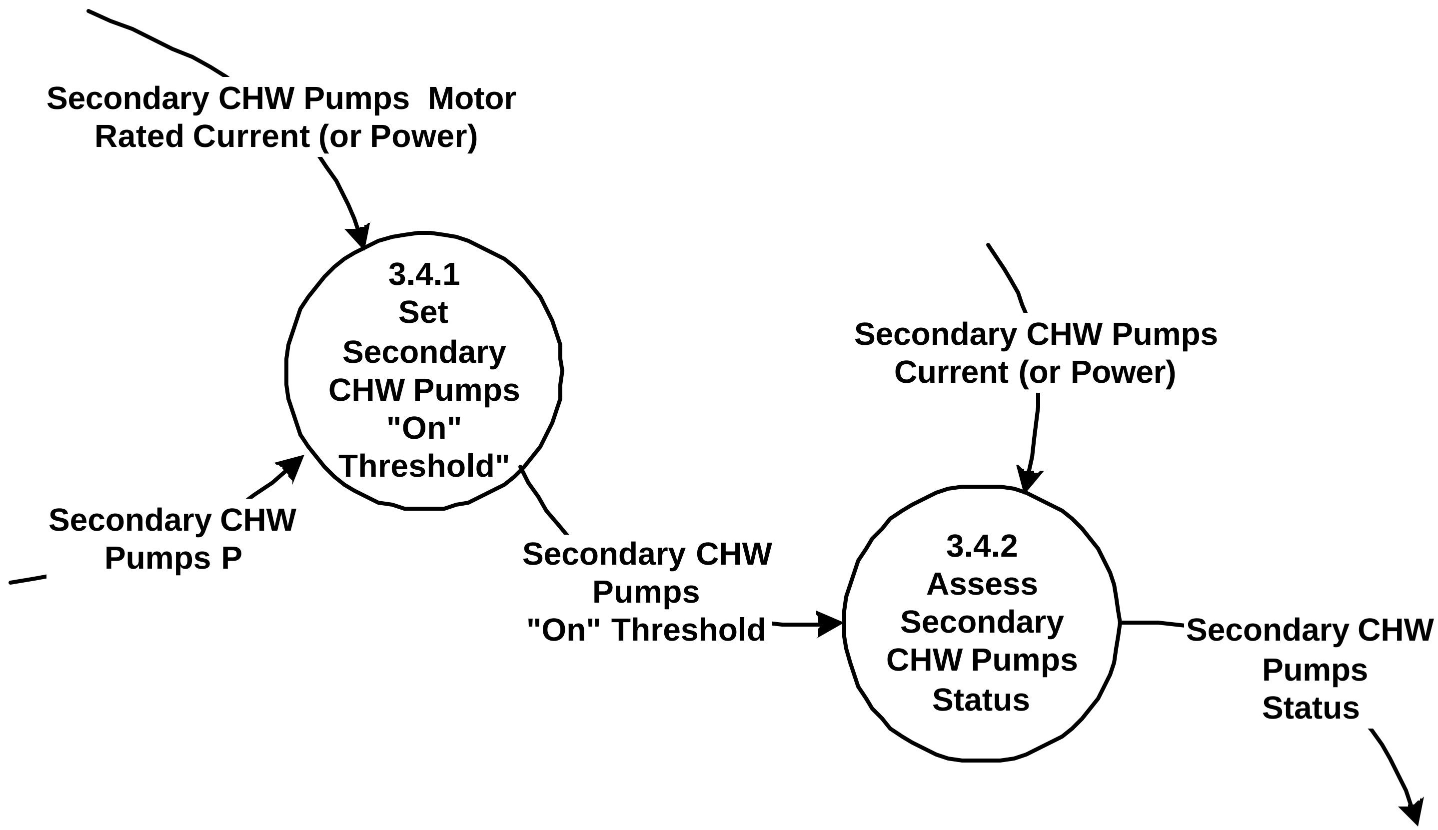
For each value of CHW Pumps Current (or Power),

compare CHW Pumps Current (or Power) to the CHW Pumps "On" Threshold.

If the value of CHW Pumps Current (or Power) <= CHW Pumps "On" Threshold, then set CHW Pumps Status = "off."

If the value of CHW Pumps Current (or Power) > CHW Pumps "On" Threshold, then set CHW Pumps Status = "On."

3.4 Determine Secondary CHW Pumps Status



3.4.1 Set Secondary CHW Pumps "On" Threshold"

Calculate the Secondary CHW Pumps "On" Threshold using

Secondary CHW Pumps "On" Threshold = Secondary CHW Pumps P x Secondary CHW Pumps Motors Rated Current (or Power)

Notes:

Secondary CHW Pumps P has values that range from 10 to 50% -- this can be a user input.

3.4.2 Assess Secondary CHW Pumps Status

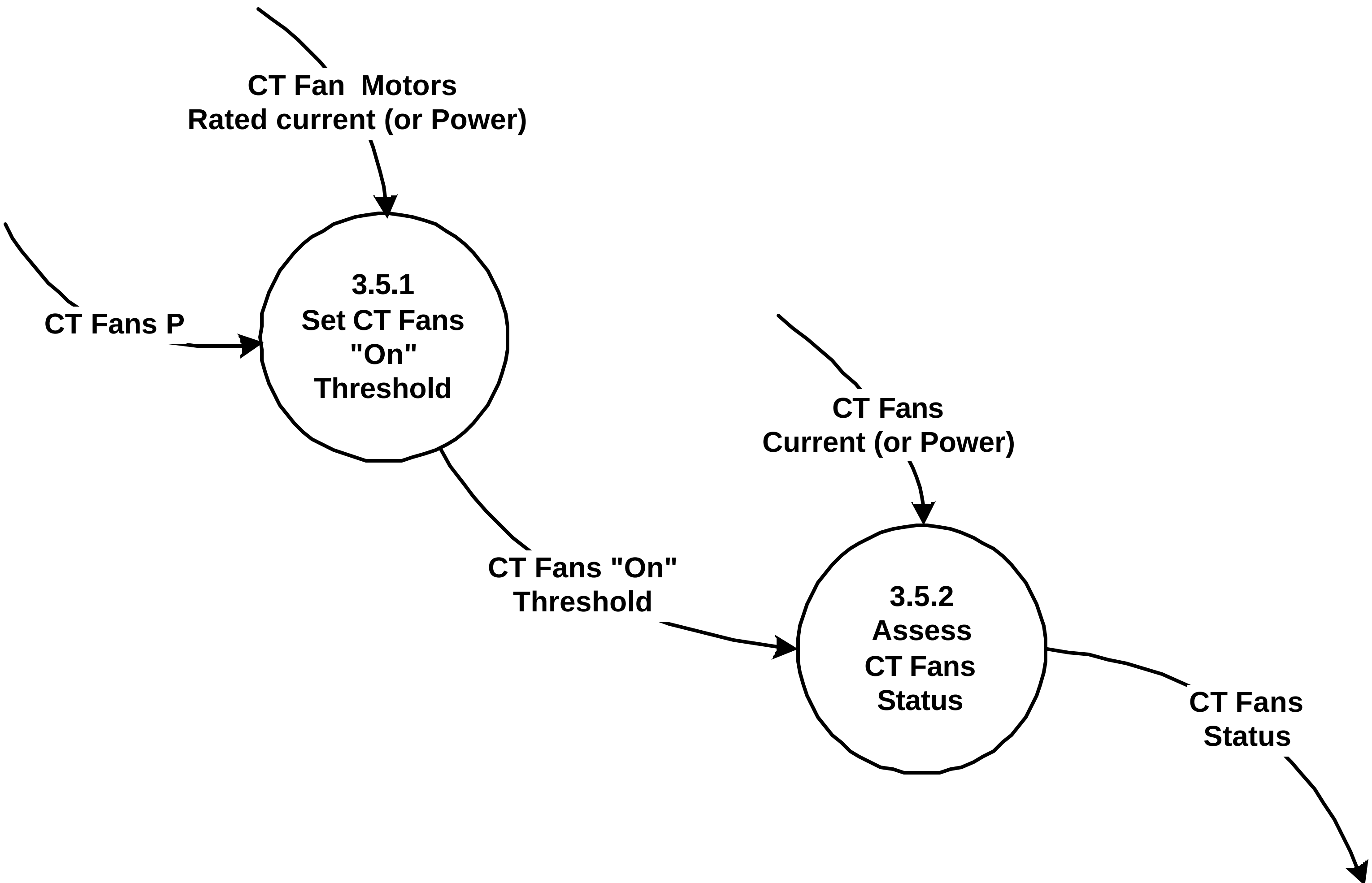
For each value of Secondary CHW Pumps Current (or Power),

compare Secondary CHW Pumps Current (or Power) to the Secondary CHW Pumps "On" Threshold.

If the value of Secondary CHW Pumps Current (or Power) <= Secondary CHW Pumps "On" Threshold, then set Secondary CHW Pumps Status = "off."

If the value of Secondary CHW Pumps Current (or Power) > Secondary CHW Pumps "On" Threshold, then set Secondary CHW Pumps Status = "On."

3.5 Determine CT Fans Status



3.5.1 Set CT Fans "On" Threshold

Calculate the CT Fans "On" Threshold using

CT Fans "On" Threshold = CT Fans P x CT Fan Motors Rated Current (or Power)

Notes:

CT Fans P has values that range from 10 to 50% -- this can be a user input.

3.5.2 Assess CT Fans Status

For each value of CT Fans Current (or Power),

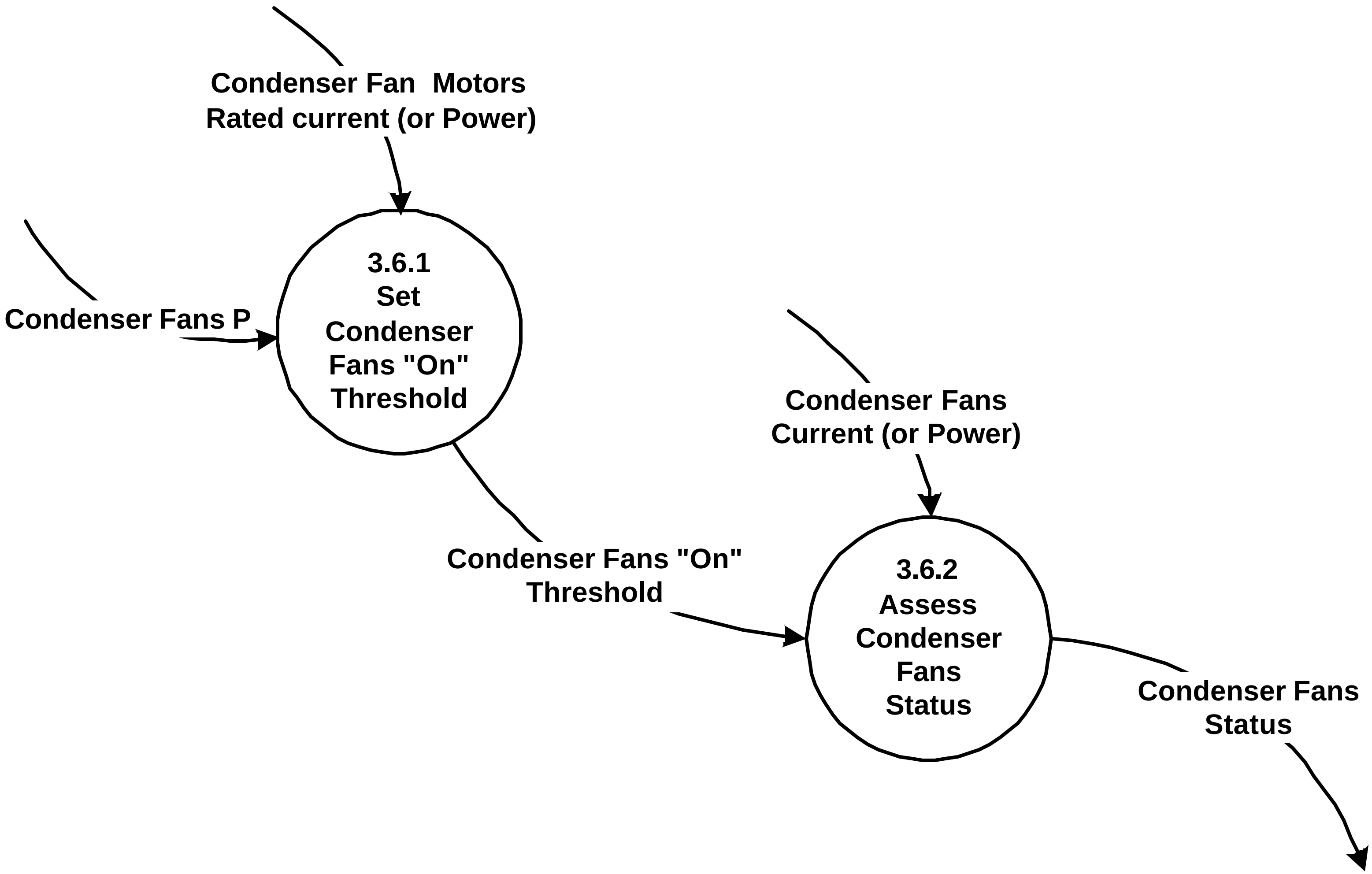
compare CT Fans Current (or Power) to the CT Fans "On" Threshold.

If the value of CT Fans Current (or Power) <= CT Fans "On" Threshold, then set CT Fans Status = "Off."

If the value of CT Fans Current (or Power) > CT Fans "On" Threshold, then set CT Fans Status = "On."

Note:

3.6 Determine Condenser Fans Status



3.6.1 Set Condenser Fans "On" Threshold

Calculate the Condenser Fans "On" Threshold using

Condenser Fans "On" Threshold = Condenser Fans P x Condenser Fan Motors Rated Current (or Power)

Notes:

Condenser Fans P has values that range from 10 to 50% -- this can be a user input.

3.6.2 Assess Condenser Fans Status

For each value of Condenser Fans Current (or Power),

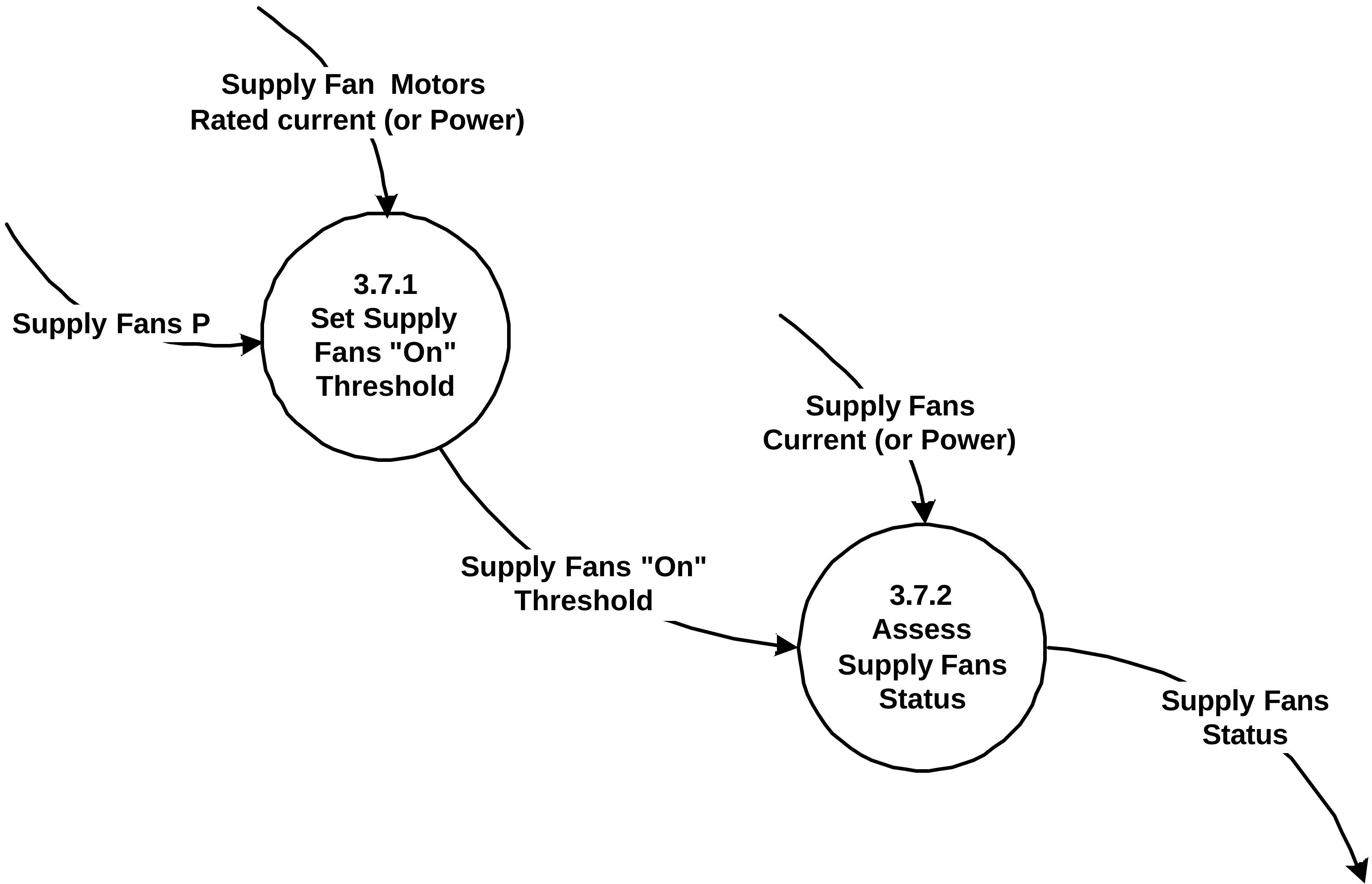
compare Condenser Fans Current (or Power) to the Condenser Fans "On" Threshold.

If the value of Condenser Fans Current (or Power) <= Condenser Fans "On" Threshold, then set Condenser Fans Status = "Off."

If the value of Condenser Fans Current (or Power) > Condenser Fans "On" Threshold, then set Condenser Fans Status = "On."

Note:

3.7 Determine Supply Fans Status



3.7.1 Set Supply Fans "On" Threshold

Calculate the Supply Fans "On" Threshold using

Supply Fans "On" Threshold = Supply Fans P x Supply Fan Motors Rated Current (or Power)

Notes:

Supply Fans P has values that range from 10 to 50% -- this can be a user input.

3.7.2 Assess Supply Fans Status

For each value of Supply Fans Current (or Power),

compare Supply Fans Current (or Power) to the Supply Fans "On" Threshold.

If the value of Supply Fans Current (or Power) <= Supply Fans "On" Threshold, then set Supply Fans Status = "Off."

If the value of Supply Fans Current (or Power) > Supplyr Fans "On" Threshold, then set Supply Fans Status = "On."

Note:

5. Appendix B: Chiller, Cooling Tower, and Chilled-Water Distribution Data Dictionary

Variable	Definition	Values
Ambient wb Temperature	Ambient wet-bulb temperature of the outdoor air. Equivalent to the Outdoor-Air Wet-Bulb Temperature and Outdoor-Air Temperature Wet-Bulb (OATWB)	Temperature in degrees F.
Ambient Wet-Bulb Temperature (OATWB)	Wet-bulb temperature of the outdoor air. Equivalent to Outdoor-Air Wet-Bulb Temperature and Outdoor-Air Temperature Wet Bulb (OATWB)	Temperature in degrees F.
Ambient-Air Temperature (OAT)	Equivalent to Outdoor-Air Temperature (OAT) and is the dry-bulb temperature of the ambient outdoor air.	Temperature in degrees F.
Chiller "On" Threshold	The value of Chiller Current (or Chiller Power) above which the Chiller Status is considered "On."	On.
Chiller Condenser Type	The type of cooling for the chiller condenser. It takes values of “Water cooled” or “Air cooled”	Water cooled or air cooled.
Chiller On/off Status	An indicator of whether the chiller is on or off. Chiller on/off Status = Compressor on/off Status.	On or off.
Chiller Schedule	Schedule of chiller on and off times during a day. The schedule may vary based on day of week, type of day (e.g., weekday vs. weekend vs. holiday), or time of year. The schedule does not take into account chiller cycling, which may be caused by changes in load during a scheduled "on" time period.	Absolute On/off times
Chiller Schedule Ok/not	Indicator of whether the chiller is operating only during scheduled times or not.	Ok. Not Ok. The chiller is operating outside its scheduled time.
Chiller Status	Same as Chiller On/off Status. An indicator of whether the chiller is on or off. Takes values of "on" or "off." Chiller status = Compressor status.	On or off.
Chiller System Type	The type of chiller system. Chiller System	Water cooled or air cooled.
Chiller/Compressor Start-Up Time	Estimated time over which the compressor current/power spikes after the compressor is turned from off to on. This could be estimated manually and entered by the user or might be derived automatically from compressor data in a separate process (not yet specified in this model).	Time difference in minutes.

Variable	Definition	Values
CHWdDown	The maximum temperature increment below the CHW Setpoint which when subtracted from the CHW Setpoint results in the minimum acceptably-controlled CHW Temperature.	Temperature difference in degrees F.
CHWdUp	The maximum temperature increment above the CHW Setpoint which when added to the CHW Setpoint results in the maximum acceptably-controlled CHW Temperature.	Temperature difference in degrees F.
CHW Pumps Collective Status	The status of all the primary chilled water pumps in an associated set taken as a single unit. If at least one pump of the set is ON, the collective status is ON. If all the pumps in the set are OFF, the collective status is OFF.	On or Off.
CHW Pumps Current (or Power)	Chilled Water Pumps Current (or Power). The measured value of current (or power) for the primary CHW pumps motor.	Current in amps.
CHW Pumps Last Time Turned On	Chilled Water Pumps Last Time Turned On. The time of the last measurement of CHW Water Pumps Status at which the CHW Pumps Status was "On" while the Preceding CHW Pumps Status was "Off."	Absolute time in minutes.
CHW Pumps Max Start-Up Time	Chilled Water Pumps Max Start-Up Time. The maximum time that the CHW Pumps should turn on before the compressor turns on. This can be set by default to 5 minutes.	Time in minutes.
CHW Pumps Motor Rated Current (or Power)	Chilled Water Pumps Motor Rated Current (or Power). Current (or power) rating of the primary CHW Pumps motor from the motor nameplate.	Current in amps.
CHW Pumps P	Chilled Water Pumps P. Fraction of Chilled Water Pumps Motor Rated Current (or Power) selected for the "On" Threshold.	None.
CHW Set Point	Chilled Water Set Point. The set point for the chilled water supply temperature.	Temperature in degrees F.
CHWST	Chilled Water Supply Temperature. Temperature of the chilled water leaving the chiller and entering the chilled water distribution system at the current time.	Temperature in degrees F.

Variable	Definition	Values
CHWST Alarm	A variable indicating the current value of the alarm for the chilled water supply temperature deviations from set point. It takes values of “Too High”, “Too Low”, and “OK”. It indicates whether the CHW temperature is maintained adequately over a designated minimum number of time steps (CHWST Alarm Interval High and CHWST Alarm Interval Low).	Too high, too low or Ok.
CHWST Alarm Evaluation Interval	The number of time steps immediately preceding the current time over which the criterion for a CHWST alarm is evaluated. This parameter takes integer values and is adjustable to change the low-alarm sensitivity. Its value may be specified as a set-up variable, default value, or empirically adjustable.	Number of time steps.
CHWST Alarm Trigger High	The minimum fraction of values of the variable CHWST Maintained OK/not that are equal to "Too High", when evaluated over CHWST Alarm Evaluation Interval time steps, for a high alarm to be reported, i.e., for CHWST Alarm to be set equal to “CHWST High.” This variable takes values between 0.51 and 1.0 (i.e., 51% and 100%). It may be a user set-up input, a default value, or a empirically adjusted sensitivity. The current process descriptions assume that High and Low alarms cannot occur simultaneously.	Real values between 0.51 and 1.00.
CHWST Alarm Trigger Low	The minimum fraction of values of the variable CHWST Maintained OK/not that are equal to "Too Low", when evaluated over CHWST Alarm Evaluation Interval time steps for an alarm to be reported, i.e., for CHWST Alarm to be set equal to “CHWST Low.” This variable takes values between 0.51 and 1.0 (i.e., 51% and 100%). It may be a user set-up input, a default value, or a empirically adjusted sensitivity.	Real values between 0.51 and 1.00.
CHWST at Last Time Off	Chilled Water Supply Temperature measured the last time the compressor was off.	Temperature in degrees F.
CHWST Deviation (Chilled Water Supply Temperature Deviation)	CHWST Deviation = CHW Temperature - CHW Setpoint. The amount by which the actual Chilled Water Supply Temperature deviates from the chilled water set point at the present time.	Temperature difference in degrees F.

Variable	Definition	Values
CHWSTFraction High	CHWSTFraction High = CHWSTNumber High/(CHWST Alarm Evaluation Interval). This is the fraction of the total number of time steps during the CHWST Alarm Evaluation Interval that have “Too High” as the value for the variable CHWST Maintained OK/not.	Dimensionless real number between 0.0 and 1.0.
CHWSTFraction Low	CHWSTFraction Low = CHWSTNumber Low/(CHWST Alarm Evaluation Interval). This is the fraction of the total number of times steps during the CHWST Alarm Evaluation Interval that have “Too Low” as the value for the variable CHWST Maintained OK/not.	Dimensionless real number between 0.0 and 1.0.
CHWST Last	The value of the Chilled Water Supply Temperature (CHWST) corresponding to the last measurement time immediately preceding the current measurement time.	Temperature in degrees F.
CHWST Lower Bound	Chilled Water Supply Temperature Lower Bound = CHW Setpoint - (CHWdDown). It is the minimum CHW temperature considered acceptably controlled.	Temperature difference in degrees F.
CHWST Maintained OK/not (Chilled Water Supply Temperature Maintained OK/not)	Chilled Water Supply Temperature Maintained OK/not is a variable indicating whether the CHW temperature is maintained adequately at a specific point in time (i.e., time step). It takes values of: "OK," "too high," and "too low."	Ok, too high, or too low.
CHWST Maintained OK/not Array	The array: {CHWST Maintained OK/not, CHWST Maintained OK/not (1 time step ago), CHWST Maintained OK/not (2 time steps ago), CHWST Maintained OK/not (3 time steps ago), CHWST Maintained OK/not (4 time steps ago), CHWST Maintained OK/not [(CHWST Alarm Evaluation Interval – 1) time steps ago]}	Array with individual elements takings values of Ok or Not OK.
CHWST Mean Too-High Deviation	Arithmetic mean value of the CHWST Deviation for times included in the CHWST Maintained OK/not Array for which CHWST Maintained OK/not is “Too High”.	Temperature in degrees F.
CHWST Mean Too-Low Deviation	Arithmetic mean value of the CHWST Deviation for times included in the CHWST Maintained OK/not Array for which CHWST Maintained OK/not is “Too Low”.	Temperature in degrees F.
CHWSTNumber High	CHWSTNumber High is the number of values of the variable CHWST Maintained OK/not with values of “Too High” during the last CHWST Alarm Evaluation Interval time steps.	Integer.

Variable	Definition	Values
CHWSTNumber Low	CHWSTNumber Low is the number of values of the variable CHWST Maintained OK/not with values of "Too Low" during the last CHWST Alarm Evaluation Interval time steps.	Integer.
CHWST Upper Bound	Chilled Water Supply Temperature Upper Bound = CHW Setpoint + (CHWdup). It is the maximum CHW temperature considered acceptably controlled.	Temperature in degrees F.
CHW Temperature	Chilled Water Temperature. Same as Chilled Water Supply Temperature.	Temperature in degrees F.
CHW Transient Decrease Factor	Fraction of the difference between the Chilled Water Supply Temperature (CHWST) at Last Off Time and the CHWST Setpoint that is used to determine the Minimum Transient Decrease in CHWST. It takes values between 0 and 1.0 and may be a user (setup) input, a default value, or a value determined empirically during diagnosis (i.e. use of the diagnostic tool).	Dimensionless real number between 0.0 and 1.0
Compressor "On" Threshold	The value of Compressor Current (or Compressor Power) above which the Compressor is considered "on." Used to determine if the chiller is "on."	Current in amps.
Compressor Current (or Power)	The measured value of current (or power) at the current time for the compressor motor.	Current in amps.
Compressor Interlocked With CHW Pumps OK/not	An indicator of whether the compressor and the CHW Pumps are properly interlocked or not. It takes values of "OK" and "Not OK."	OK Not OK.
Compressor Interlock with Condenser Fans OK/Not	An indicator of whether the compressor and the Condenser Fans are properly interlocked or not. It takes values of "OK" and "Not OK."	OK Not OK.
Compressor Interlocked With Condenser Pumps OK/not	An indicator of whether the compressor and the Condenser Pumps are properly interlocked or not. It takes values of "OK" and "Not OK."	OK Not OK.
Compressor Motor Rated Current (or Power)	Current (or power) rating of the compressor motor from the motor nameplate.	Current in amps.
Compressor Off Cycle OK/not	An indicator of whether the compressor is meeting the Minimum Compressor Off Time while cycling between off and on. It takes values of "OK" and "Not OK."	OK Not OK.

Variable	Definition	Values
Compressor On Cycle OK/not	An indicator of whether the compressor is meeting the Minimum Compressor On Time while cycling between on and off. It takes values of “OK” and “Not OK.”	OK Not OK.
Compressor On/off Status	Same as Compressor status. An indicator of whether the compressor is on or off. Takes values of "on" or "off." Chiller on/off Status = Compressor on/off Status.	On or off.
Compressor P	Fraction of Compressor Motor Rated Current (or Power) selected for the "On" Threshold	Dimensionless real number between 0.0 and 1.0.
Compressor State	An indicator of whether the chiller is in an off, a transient, or a steady state, where the difference between steady and transient operation is indicated by the rate of change of the chilled water supply temperature (CHWST). Takes values of “Off,” “Transient,” or “Steady.”	Off, transient, or steady.
Compressor Status	Same as Compressor On/off Status. An indicator of whether the compressor (and, therefore the chiller) is on or off. Takes values of "on" or "off” as indicated by the Compressor Current. Also indicates Chiller Status, i.e., Chiller Status = Compressor Status.	On or off.
Condenser Fan Motors Rated Current (or Power)	Current (or power) rating of the condenser fan motors from the motor nameplates.	Current in amps.
Condenser Fans P	Fraction of Condenser Fan Motors Rated Current (or Power) selected for the "On" Threshold.	Dimensionless real number between 0.0 and 1.0.
Condenser Fans "On" Threshold	The value of Condenser Fans Current (or Power) above which the condenser fans are considered "on." Used to determine if the condenser fans are "on."	Current in amps.
Condenser Fans Current (or Power)	For air-cooled condensers, the measured value of current (or power) for the condenser fans	Current in amps.
Condenser Fans Status	For air-cooled chillers, an indicator of whether the condenser fans is (are) on or off. Takes values of "on" or "off."	On or off.
Condenser Pumps P	Fraction of Condenser Pump Motors Rated Current (or Power) selected for the "On" Threshold	Current in amps.

Variable	Definition	Values
Condenser Pumps "On" Threshold	The value of Condenser Pumps Current (or Power) above which the Condenser Pumps are considered "on." Used to determine if the condenser pumps are "on."	Current in amps.
Condenser Pumps Current (CPC)	The measured value of the electric current to the chiller condenser pumps at the current time.	Current in amps.
Condenser Pumps Current (CPC)	The measured value of the electric current to the chiller condenser pumps at the current time.	Current in amps.
Condenser Pumps Current (or Power)	Same as CPC.	Current in amps.
Condenser Pumps Last Time Turned On	The time of the last measurement of Condenser Pumps Status at which the Condenser Pumps Status was "On" while the Preceding Condenser Pumps Status was "Off."	Time in minutes.
Condenser Pumps Max Start-Up Time	The maximum time that the condenser pumps should turn on before the compressor turns on. This can be set by default to 5 minutes.	Time in minutes.
Condenser Pumps Status	Variable indicating whether the condenser pumps are on or off	On or Off.
Condenser Type	Takes values of "water cooled" or "air cooled."	Water cooled or air cooled.
Condenser-Pumps Motor Rated Current (or Power)	Current (or power) rating of the condenser pumps motor from the motor nameplate.	Current in amps.
CT Approach Benchmark	An indicator of the maximum CT approach acceptable for the cooling tower when providing maximum cooling (i.e., when the sump temperature is at or above the setpoint and the fans running continuously). Assumed to be available as a user input based on: 1) the control specification or 2) the manufacturer's specification.	Temperature difference in degrees F.
CT Cycling OK/Not	Variable that indicates whether the cycling of the cooling tower fans is OK or not. If it cycles too frequently, the fan motors may be damaged reducing their lives.	OK or Not OK.

Variable	Definition	Values
CT Fan Motors Rated Current (or Power)	Cooling Tower Fan Motors Rated Current (or Power). Current (or power) rating of the cooling tower fan motors from the motor nameplates.	Current in amps.
CT Fans Current (or Power	Cooling Tower Fans Current (or Power). The measured value of the electrical current (or power) to the cooling tower fan motors at the current time.	Amps.
CT Fans "On" Set Point	The cooling tower "on" set point = the value of the sump temperature above which the cooling tower fans are turned on.	Temperature in degrees F.
CT Fans "On" Threshold	Cooling Tower Fans "On" Threshold. The value of Cooling Tower Fans Current (or Power) above which the cooling tower fans are considered "on." Used to determine if the cooling tower fans are "on."	Current in amps.
CT Fans "Off" Set Point	The cooling tower "off" set point = the value of the sump temperature below which the cooling tower fans are turned off.	Temperature in degrees F.
CT Fans P	Cooling Tower Fans P. Fraction of Cooling Tower Fan Motors Rated Current (or Power) selected for the "On" Threshold.	Current in amps.
CT Fans Staging OK/Not	Variable indicating whether the fan staging is Ok or not.	"OK (as far as we can tell)." "OK." "Not OK. There is a fan staging problem and the cooling tower is not maintaining the Sump Temp as low as it could/should." "Not OK. There is a fan staging problem and energy is being wasted. All CT Fans should be off."
CT Fans Status	Cooling Tower Fans Status. For water cooled chillers, a variable indicating whether the cooling tower fans are on or off. Takes values of "on" or "off."	On or Off.
CT Fans/Condenser Pumps Interlock OK/Not	An indicator of whether the cooling tower fans and the condenser pumps are properly interlocked or not.	OK or Not OK.

Variable	Definition	Values
CT Inlet Temperature	Temperature of the cooling water entering the cooling tower. This temperature will be very close to the temperature of the water leaving the condenser of the chiller.	Temperature in degrees F.
CT Range	Cooling Tower Range = The difference between the temperature of the water entering the cooling tower (cooling tower inlet temperature) and the temperature of the water leaving the cooling tower (outlet temperature).	Temperature difference in degrees F.
CT Range Benchmark	Benchmark for comparison of calculated values of the CT range (may be a user input based on the control spec, specified by the manufacturer or determined by analysis of operating data. TBD)	Degrees F.
CT Range OK/Not	Variable indicating whether the CT range calculated from measurements is equal or greater than the expected range (given by the CT Range Benchmark), in which case it is OK, or whether it is less than expected, in which case it is not OK because the cooling tower is transferring less heat at maximum capacity than expected.	OK or Not OK. There is a problem with CT heat rejection and it is performing at less than expected capacity.
CT Sump Temp Setpoint	The setpoint for the water in the cooling tower sump, i.e., the temperature setpoint for the water leaving the cooling tower.	Temperature in degrees F.
CT Sump Temperature	The temperature of the cooling tower sump, which is the same as the temperature of the water leaving the cooling tower of the cooling tower outlet temperature.	Temperature in degrees F.
Current Time	The time of the current time step	Time in minutes.
Identification of Condition	This data flow represents the collection of all output data from the diagnostic process(es), which characterize the condition of the equipment/systems undergoing diagnosis. This term is only used on the chiller context diagram. All other diagrams show individual data flows.	
Last Chilled Water Pumps Status (Last CHW Pumps Status)	The value of the CHW Pumps Status at the measurement time immediately preceding the current measurement time (i.e., at the last measurement time).	On or Off

Variable	Definition	Values
Last Chiller Status	The value of Chiller Status at the measurement time immediately preceding the current measurement time (i.e., the last measurement time). Last Chiller Status = Last Compressor Status.	On or Off
Last CHWST for Compressor "On" Time	Chilled Water Supply Temperature corresponding to the last measurement time when the compressor was on immediately preceding the current measurement time.	Temperat ure in degrees F.
Last Compressor Off Interval	The length of time the compressor was off the last time it was off. Last Compressor Off Interval = Last Compressor Switch On Time – Last Compressor Switch Off Time. Only evaluated when the compressor is currently on.	Time difference in minutes.
Last Compressor Switch Off Time	The last time at which the Compressor turned off, i.e., the last measurement time at which the Compressor Status changed from “On” to “Off.”	Time in minutes.
Last Compressor On Interval	The length of time the compressor was on the last time it was on. Last Compressor On Interval = Last Compressor Off Time – Last Compressor On Time. Only evaluated when the compressor is currently off.	Time difference in minutes.
Last Compressor Switch On Time	The last time at which the Compressor turned on, i.e., the last measurement time at which the Compressor Status changed from “Off” to “On.”	Time in minutes.
Last Compressor State	The value of Compressor State at the measurement time immediately preceding the current measurement time (i.e., the last measurement time).	Time in minutes.
Last Compressor Status	The value of Compressor Status at the measurement time immediately preceding the current measurement time (i.e., the last measurement time). Last Compressor Status = Last Chiller Status.	Time in minutes.
Last Condenser Pumps Status	The value of Condenser Pumps Status at the measurement time immediately preceding the current measurement time (i.e., the last measurement time).	Time in minutes.
Last CT Fan Off Interval	The length of time the CT fans were off the last time they were off. Last CT Fan Off Interval = Last CT Fans On Time – Last CT Fans Off Time. Only evaluated when the compressor is currently on.	Time difference in minutes.

Variable	Definition	Values
Last CT Fans Off Time	The last time at which the CT Fans turned on, i.e., the last measurement time at which the CT fans status changed from “Off” to “On.”	Absolute time in minutes.
Last CT Fans On Time	The last time at which the CT Fans turned off, i.e., the last measurement time at which the CT fans status changed from “On” to “Off.”	Absolute time in minutes.
Last CT Fans Status	The value of the CT fans status at the measurement time immediately preceding the current measurement time (i.e., at the last measurement time).	On or Off.
Last Fans On Interval	The length of time the CT fans were on the last time they were on. Last CT Fan On Interval = Last CT Fans Off Time – Last CT Fans on Time. Only evaluated when the compressor is currently off.	Time difference in minutes.
Measurement Time	The time at which measured (or metered) data are collected.	Time in minutes.
Metered Data	The collection of all input data that is collected periodically from sensors or observations. Values of metered data are updated periodically at the measurement frequency. It can be contrasted with set-up data, which is generally collected only once. Metered data is generally used to characterize the condition (or state) of the equipment and systems at a particular point in time. This term is used only on the chiller context diagram. All other diagrams show individual data flows.	
Min. CT Fans Off Time	The minimum permissible time increment that the cooling tower fans should be off before being turned on again in order to prevent damage to the fan motors during fan cycling, as specified by the manufacturer.	Time in minutes.
Min. CT Fans On Time	The minimum permissible time increment that the cooling tower fans should be on before being turned off again in order to prevent damage to the fan motors during fan cycling, as specified by the manufacturer.	Time in minutes.

Variable	Definition	Values
Minimum Compressor Off Time	The minimum time specified by the manufacturer (or other authority) that the compressor should be off before being turned back on again.	Time in minutes.
Minimum Compressor On Time	The minimum time specified by the manufacturer (or other authority) that the compressor should be on before being turned back off again.	Time in minutes.
Minimum Transient Decrease in CHWST	The minimum transient decrease in the chilled water supply temperature. This is the minimum change in chilled water supply temperature between two sequential measurement times that would be judged as corresponding to a transient compressor state. All values of the change in CHWST between two successive measurement times would be judged as corresponding to a steady state for the compressor.	Temperature difference in F.
OAT Steady State CHW	Outdoor-Air Temperature while the Chilled Water Temperature is in a steady state, i.e., when Compressor State = Steady.	Temperature in degrees F.
Outdoor-Air Temperature (OAT)	Equivalent to Ambient-Air Temperature (OAT) and is the dry-bulb temperature of the ambient outdoor air.	Temperature in degrees F.
Outdoor-Air Temperature Wet Bulb (OATWB)	Wet-bulb temperature of the outdoor air. Equivalent to Ambient Wet-Bulb Temperature and Outdoor-Air Wet-Bulb Temperature	Temperature in degrees F.
Outdoor-Air Wet-Bulb Temperature (OATWB)	Wet-bulb temperature of the outdoor air. Equivalent to Ambient Wet-Bulb Temperature and Outdoor-Air Temperature Wet Bulb (OATWB)	Temperature in degrees F.
Passed (Filtered) CT Approach	Values of the CT approach for times when the condenser pumps status is “on”	Temperature difference in degrees F
Passed (Filtered) Ambient wb Temp	Values of the Ambient wb temperature for times when the condenser pump status is “on”	Temperature in degrees F.
Passed (Filtered) CT Sump Temp	Values of the sump temperature for times when the condenser pumps are on.	Temperature in degrees F
Passed (Filtered) CT Range	Values of the CT range for times when the condenser pumps status is “on”	Temperature difference in degrees F
Passed (Filtered) CT Fans Current	Values of the Fans Current for times when the condenser pumps are on.	Current in amps

Variable	Definition	Values
Passed (Filtered) CT Fans Current	Values of the CT Fans Current occurring when the Condenser Pumps status is “on” (i.e., belong to triplets for which Condenser Pumps Status = On).	Current in amps
Passed (Filtered) CT Fans Status	Values of the CT Fans Status occurring when the Condenser Pumps status is “on” (i.e., belong to triplets for which Condenser Pumps Status = On).	On Off
Passed Ambient wb Temp Points for Condenser Pumps On, CT Fans Status On, and Sump Temp Above the CT Fans "On" Setpoint	Values of the ambient wb temperature for times when the condenser pumps are on, the CT fans status is on, and the sump temperature is above its setpoint	Temperature in degrees F.
Passed CT Range for Condenser Pumps On, CT Fans Status On, and Sump Temp Above the CT Fans "On" Setpoint	Values of the CT Range for times when the condenser pumps are on, the CT fans status is on, and the sump temperature is above its setpoint	Temperature difference in degrees F
Preceding Condenser Pumps Status	The Condenser Pumps Status at the measurement time immediately preceding the measurement time to which reference is made.	On or Off.
Rejected Ambient wb Temp Points for CT Fans Status Off and/or for Sump Temp Below the CT Fans "On" Setpoint	Values of the ambient temperature that correspond to times when the condenser pumps are on and either or both the CT fans status are off or the sump temperature is below or equal to its setpoint.	Temperature in degrees F
Rejected Ambient wb Temp When Condenser Pumps are "Off"	Values of ambient wb temperature that correspond to times when the condenser pumps are off, which are filtered out	Temperature in degrees F
Rejected CHWST for Non-Steady CHWST	Rejected values of CHWST corresponding to times when the Compressor State = “Transient”, or Compressor State = “Off”, i.e., when the CHWST is not steady.	Temperature in degrees F.
Rejected CT Approach and Ambient wb Temp When Condenser Pumps are "Off"	Values of CT Approach and Ambient wb Temperature that correspond to times when the condenser pumps are off, which are filtered out	

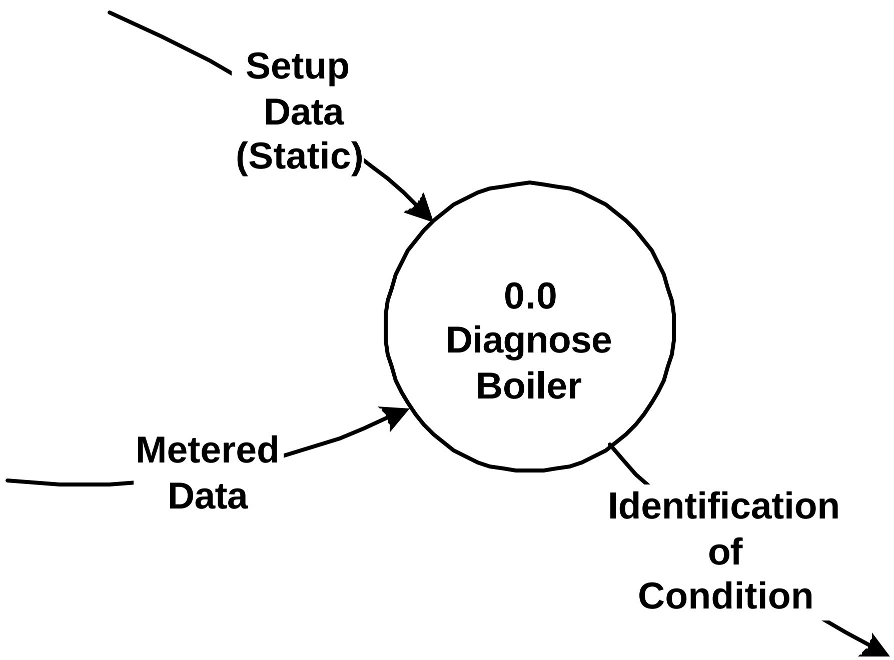
Variable	Definition	Values
Rejected CT Approach and Ambient wb Temp Points for CT Fans Status Off and/or for Sump Temp Below the CT Fans "On" Setpoint	Values of the CT Approach and ambient temperature that correspond to times when the CT fans status is “off” and/or the sump temperature is below the CT Fans “On” set point.	
Rejected CT Fans Current When Condenser Pumps are "Off"	Values of the CT Fans Current for times when the condenser pumps are off.	Current in amps
Rejected CT Range for CT Fans Status Off and/or Sump Temp Below the CT Fans "On" Setpoint	Values of the CT Range that correspond to times when the condenser pumps are on and either or both the CT fans status is off or the sump temperature is below or equal to its setpoint.	Temperature difference in degrees F
Rejected CT Range When Condenser Pumps are "Off"	Values of CT Range that correspond to times when the condenser pumps are off, which are filtered out	Temperature difference in degrees F
Rejected CT Sump Temp When Condenser Pumps are "Off"	Values of the Sump Temperature at times when the condenser pumps are off	Temperature in degrees F
Rejected OAT for Non-Steady CHWST	Rejected values of OAT corresponding to times when the Compressor State = “Transient” or Compressor State = “Off”, i.e., when the CHWST is not steady.	Temperature in degrees F.
Secondary CHW Pumps Collective Status	The status of all the secondary chilled water pumps in an associated set taken as a single unit. If at least one pump of the set is ON, the collective status is ON. If all the pumps in the set are OFF, the collective status is OFF.	On or Off.
Secondary CHW Pumps Motor Rated Current (or Power)	Secondary Chilled Water Pumps Motor Rated Current (or Power). Current (or power) rating of the secondary CHW pump motor from the motors nameplate(s).	Current in amps.

Variable	Definition	Values
Secondary CHW Pumps "On" Threshold	The value of Secondary CHW Pumps Current (or Power) above which the secondary CHW Pumps is considered "on." Used to determine if the secondary chilled water Pumps is (are) "on."	Current in amps.
Secondary CHW Pumps P	Secondary Chilled Water Pumps P. Fraction of Secondary Chilled Water Pumps Motors Rated Current (or Power) selected for the "On" Threshold.	Dimensionless real number between 0.0 and 1.0.
Secondary CHW Pumps Current (or Power)	The measured value of current (or power) for the secondary CHW Pumps at the current time.	Current in amps.
Secondary/Primary CHW Pumps Interlock OK/not	For chilled water distribution systems with secondary CHW pumps. An indicator of whether the primary CHW pumps and the secondary CHW pumps served by it are properly interlocked or not. It takes values of "OK" and "Not OK."	Ok. Not Ok.
Set-up Data	The collection of all input data that characterizes the equipment and systems in place in the building as well as its performance. It is generally entered only once for a specific building or specific piece of equipment and can be contrasted with metered data which is collected periodically. This term is used only on the chiller context diagram. All other diagrams show individual data flows.	
Sump Temp Control OK/Not	A variable indicating whether the sump temperature control is OK or not at the current time	OK Not OK. The CT fans are off but should be on. Not OK. The CT fans are on but should be off.
Supply Fan Motors Rated Current (or Power)	Current (or power) rating of the supply fan motors from the motor nameplates.	Current in amps.
Supply Fans Status	An indicator of whether the supply fans are on or off. Takes values of "on" or "off."	On or off
Supply Fans "On" Threshold	The value of Supply Fans Current (or Power) above which the supply fans are considered "on." Used to determine if the supply fans are "on."	Current in amps.

Variable	Definition	Values
Supply Fans Current (or Power)	The measured value of current (or power) for the supply fans.	Current in amps.
Supply Fans P	Fraction of Supply Fan Motors Rated Current (or Power) selected for the "On" Threshold.	Dimensionless real number between 0.0 and 1.0.
Supply Fans/Secondary CHW Pumps Interlock OK/not	For chilled water distribution systems with secondary pumps. An indicator of whether the secondary CHW pumps and the supply fans for the air handlers served by them are properly interlocked or not. It takes values of "OK," "Not OK," and "Possible problem with supply fan control--check to see if loads in the spaces served are being met."	Ok. Not Ok. Not OK," and "Possible problem with supply fan control--check to see if loads in the spaces served are being met.
Supply Fans/ CHW Pumps Interlock OK/not	An indicator of whether the primary CHW pumps and the supply fans for the air handlers served by them are properly interlocked or not. It takes values of "OK," "Not OK," and "Possible problem with supply fan control--check to see if loads in the spaces served are being met"	Ok. Not Ok. Possible problem with supply fan control--check to see if loads in the spaces served are being met.
Total Number of Time Steps Processed	The total number of time steps for which processing has been performed since processing was started and up to the current time. It takes integer values.	Integer.
Water side Economizing	Variable that indicates whether water side economizing is used or not.	Yes No

6. Appendix C: Data Flow Diagrams for Boiler Diagnostic Processes

Context Diagram Boiler



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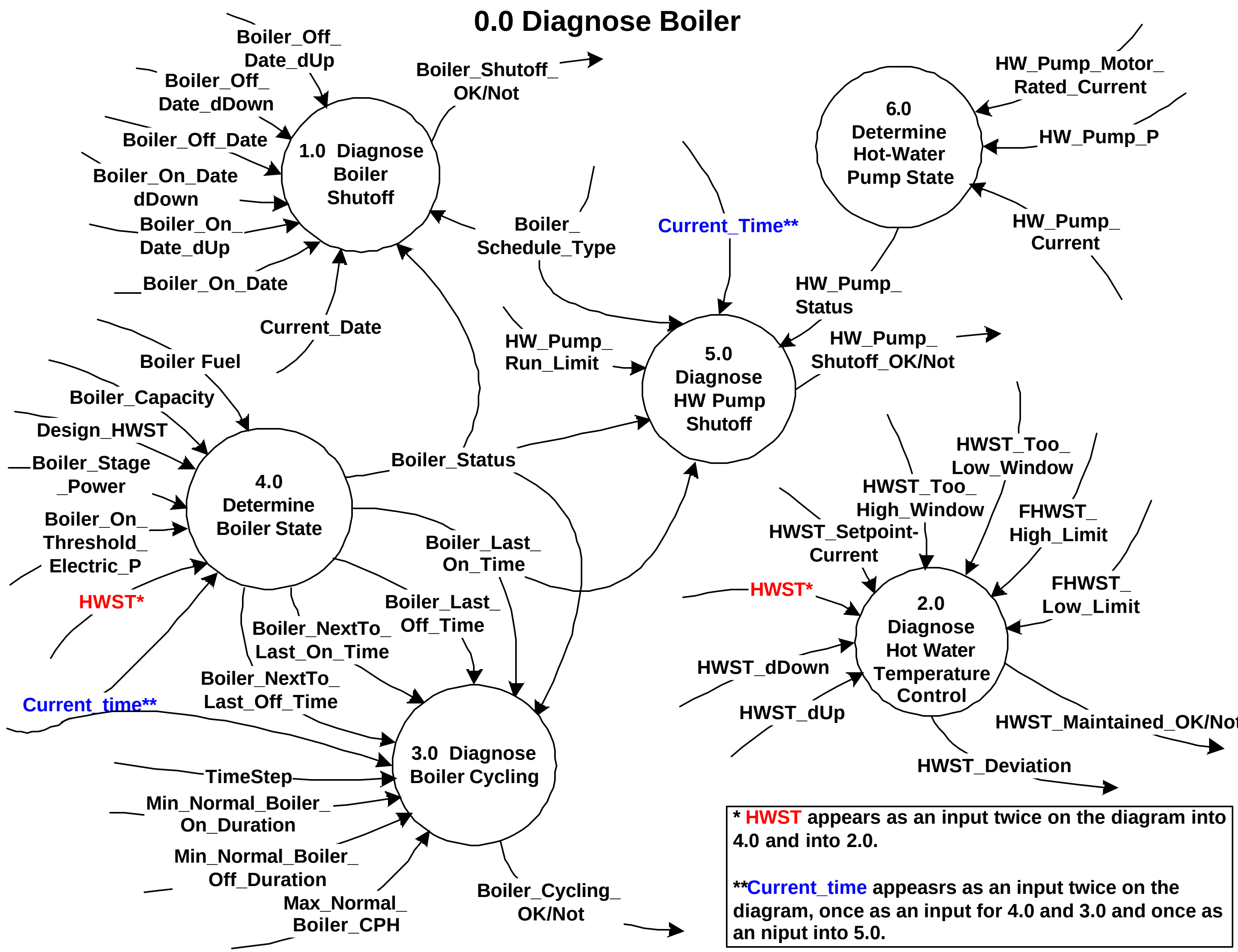
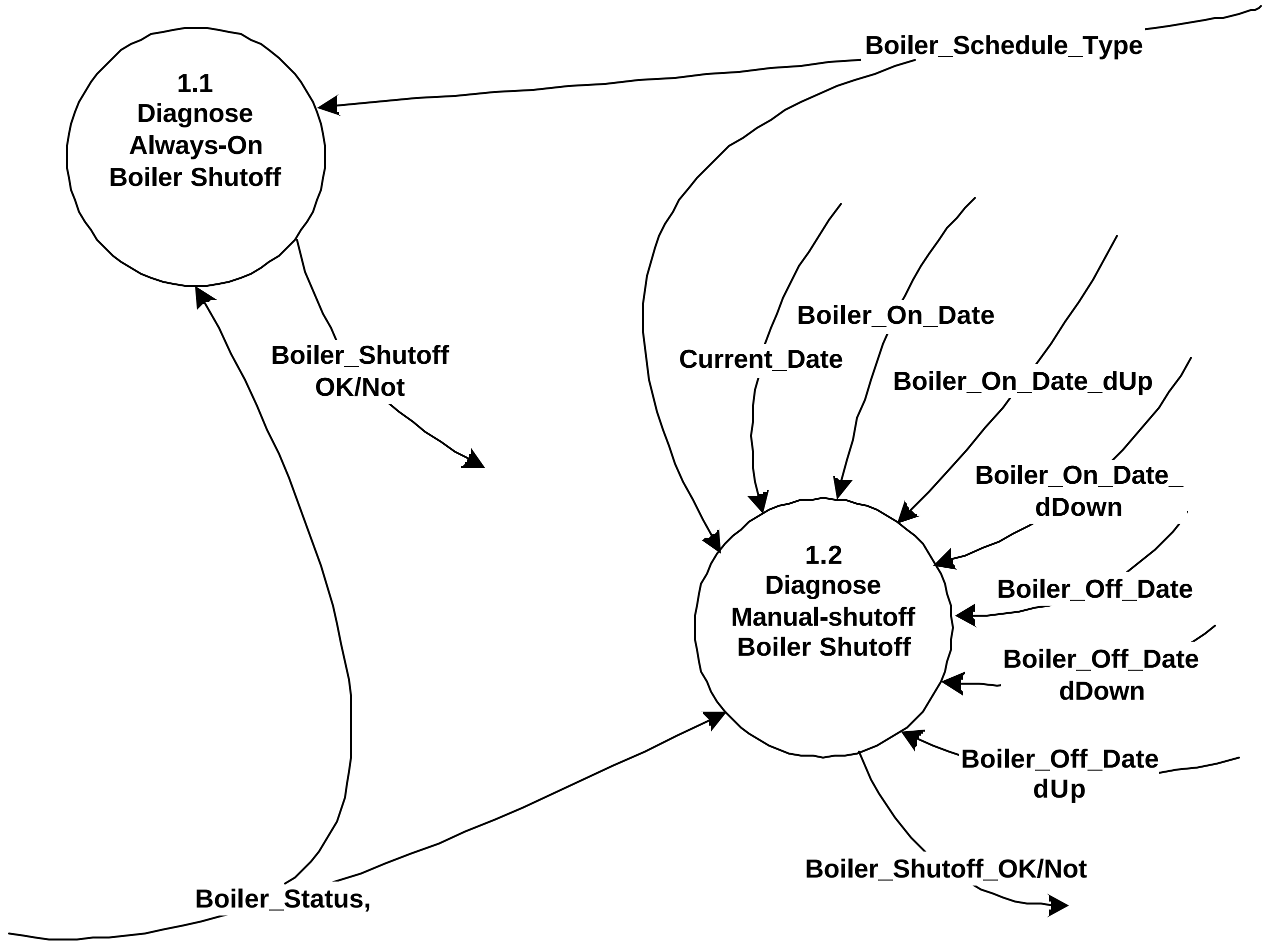


* HWST appears as an input twice on the diagram into 4.0 and into 2.0.

**Current_time appeasrs as an input twice on the diagram, once as an input for 4.0 and 3.0 and once as an niput into 5.0.

1.0 Diagnose Boiler Shutoff



Note: No diagnosis is provided for Ambient-Temperature-Based or other temperature-based boiler shutoffs. Further develelopment is required for these diagnostic procedures.

1.1 Diagnose Always-On-Boiler Shutoff

If Boiler_Schedule_Type = "Always On" AND Boiler_Status = "On"
Set Boiler_Shutoff_OK/Not = "OK. The boiler is on as it should be. Shutoff is not applicable to this boiler. The boiler system is designed for continous operation."

If Boiler_Schedule_Type = "Always On" AND Boiler_Status = "Off"
Set Boiler_Shutoff_OK/Not = "Not OK; the boiler is off and it should be on always, unless it is locked out temporarily for maintenance or repair."

1.2 Diagnose Manual-shutoff-Boiler Shutoff

If Boiler_Schedule_Type = "Manual Shutoff" AND Boiler_Status = "On"
AND if Current_Date > Boiler_On_Date + Boiler_On_Date_dUp
Set Boiler_Shutoff_OK/Not = "OK; the boiler is on as it should be."

If Boiler_Schedule_Type = "Manual Shutoff" AND Boiler_Status = "Off"
AND if Current_Date > Boiler_On_Date + Boiler_On_Date_dUp
Set Boiler_Shutoff_OK/Not = "Not OK; the boiler is off when it should be on."

If Boiler_Schedule_Type = "Manual Shutoff" AND Boiler_Status = "On"
AND if Current_Date < Boiler_Off_Date - Boiler_Off_Date_dDown,
Set Boiler_Shutoff_OK/Not = "OK; the boiler is on as it should be."

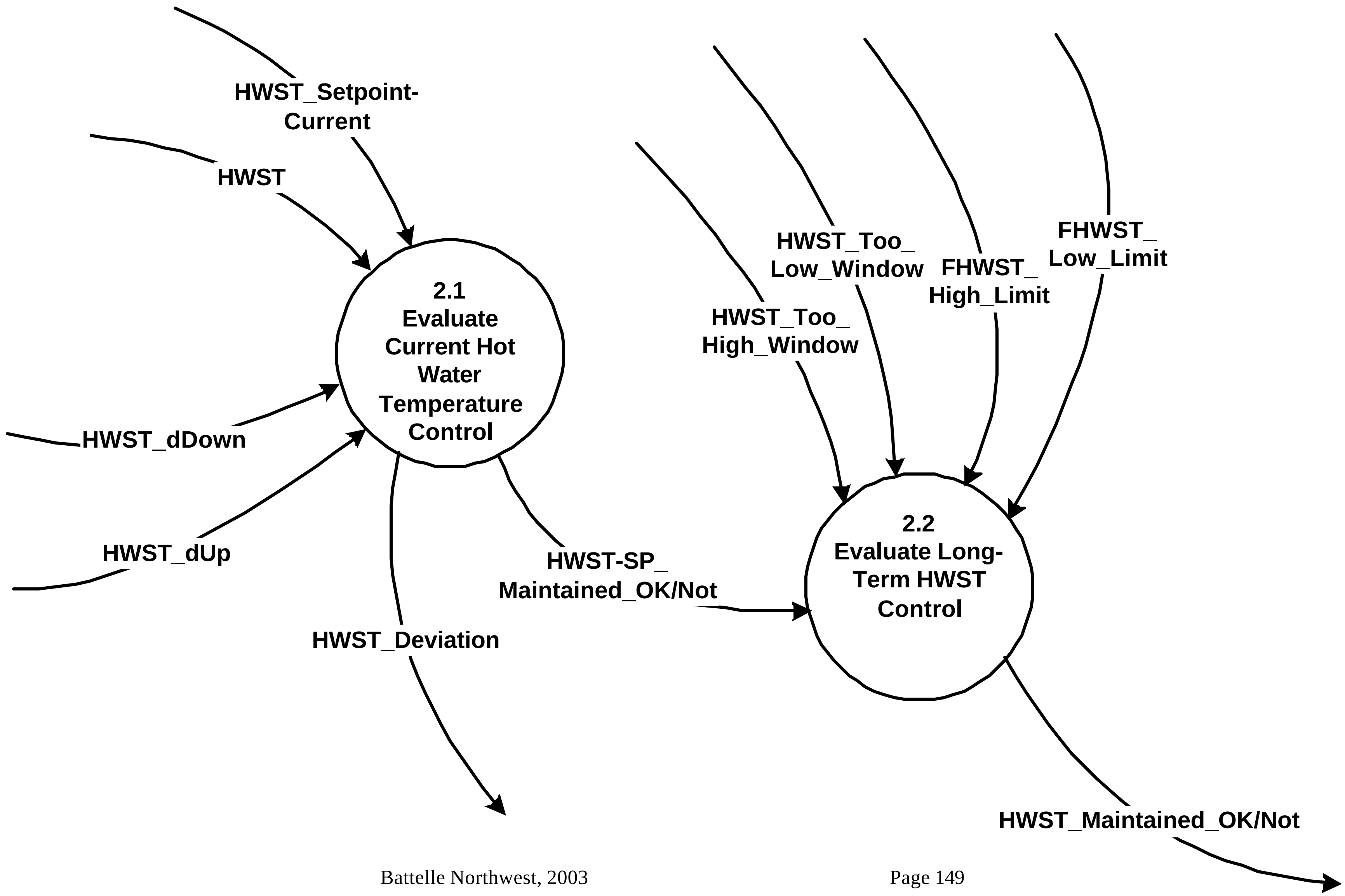
If Boiler_Schedule_Type = "Manual Shutoff" AND Boiler_Status = "Off"
AND if Current_Date < Boiler_Off_Date - Boiler_Off_Date_dDown,
Set Boiler_Shutoff_OK/Not = "Not OK; the boiler is off when it should be on."

If Boiler_Schedule_Type = "Manual Shutoff" AND Boiler_Status = "Off"
AND If Current_Date < Boiler_On_Date - Boiler_On_Date_dDown,
AND If Current_Date > Boiler_Off_Date + Boiler_Off_Date_dUp,
Set Boiler_Shutoff_OK/Not = "OK; the boiler is off as it should be"

If Boiler_Schedule_Type = "Manual Shutoff"
AND If Current_Date > Boiler_On_Date - Boiler_On_Date_dDown,
AND If Current_Date < Boiler_On_Date + Boiler_On_Date_dUp,
Set Boiler_Shutoff_OK/Not = "Ok; the date is too close to the Boiler On Date to evaluate compliance with the schedule."

If Boiler_Schedule_Type = "Manual Shutoff"
AND If Current_Date > Boiler_Off_Date - Boiler_Off_Date_dDown,
AND If Current_Date < Boiler_Off_Date + Boiler_Off_Date_dUp,
Set Boiler_Shutoff_OK/Not = "Ok; the date is too close to the Boiler Off Date to evaluate compliance with the schedule."

2.0 Diagnose Hot Water Temperature Control



2.1 Evaluate Current Hot Water Temperature

Calculate the upper bound for acceptable Hot Water Supply Temperature using

HWST Upper Bound = HWST_Setpoint-Current + HWST_dUp

Calculate the lower bound for acceptable Hot Water Supply Temperature using

HWST Lower Bound = HWST_Setpoint-Current - HWST_dDown

Compare the Hot Water Supply Temperature (HWST) to the HWST Upper Bound and HWST Lower Bound.

If HWST > HWST Upper Bound, then
Set HWST-SP_Maintained_OK/Not = "Too high" for the current time.

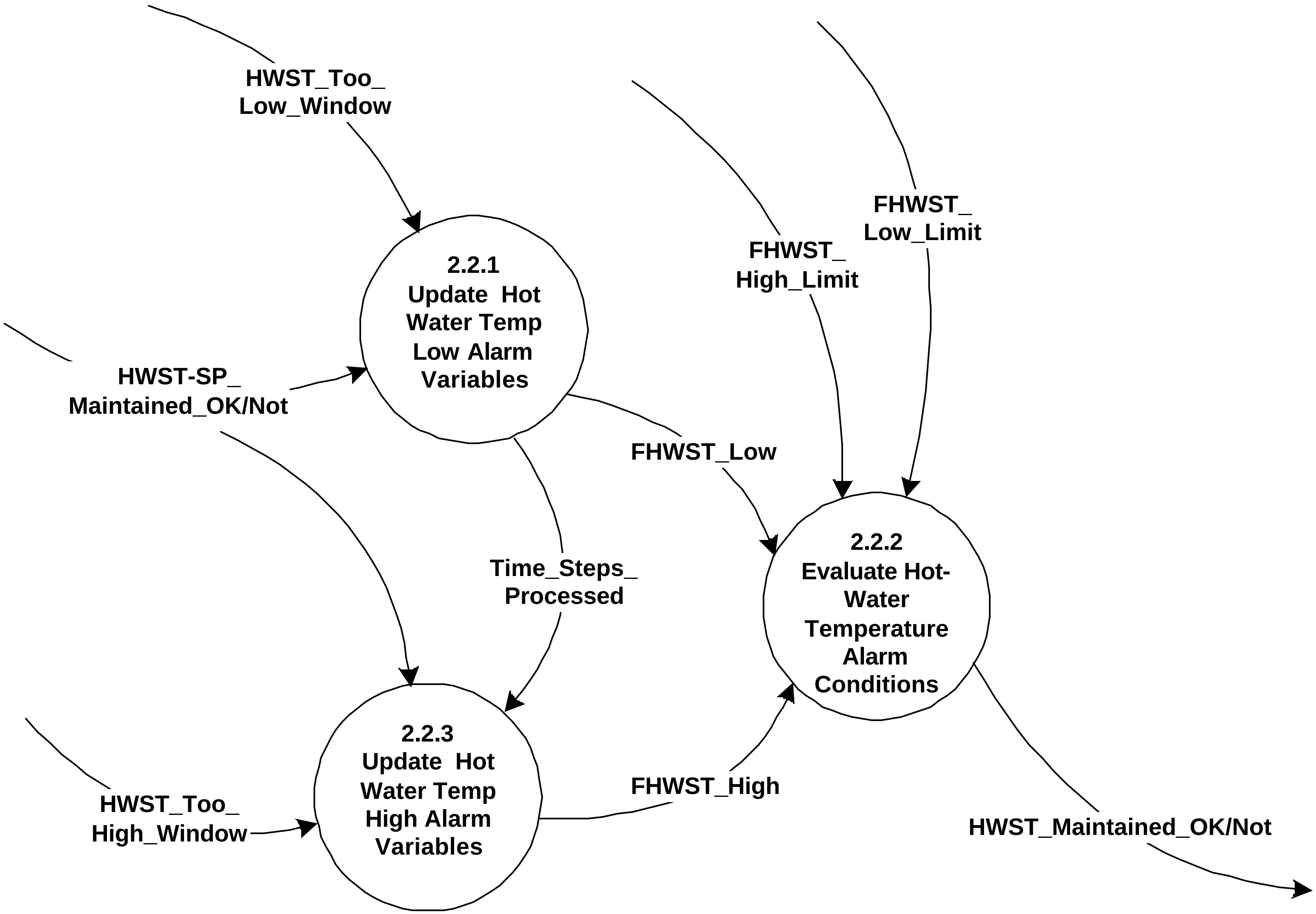
If HWST < HWST Lower Bound, then
Set HWST-SP_Maintained_OK/Not = "Too low" for the current time.

If HWST <= HWST Upper Bound, AND
HWST >= HWST Lower Bound, then
Set HWST_Maintained_OK/Not = "OK" for the current time.

Calculate the HWST Deviation for the current time

HWST_Deviation = HWST - HWST_Setpoint-Current.

2.2 Evaluate Long-Term HWST Control



2.2.1 Update Hot Water Temp Low Alarm Variables

Update the Time_Steps_Processed, using

Time_Steps_Processed = Time_Steps_Processed + 1

Update the value of FHWST_Low based on the latest value of HWST_Maintained_OK/Not.

Update the HWST_Maintained_OK/not_Too-Low_Array

Update all values in the array, adding the current value of HWST_Maintained_OK/not to the array and by dropping the oldest value of HWST_Maintained_OK/not from the array.

Update value for HWSTNumber_Low.

Set HWSTNumber_Low = number of values "Too Low" appearing in HWST_Maintained OK/Not_Too-Low_Array.

If Total_Number_of_Time_Steps_Processed < HWST_Too_Low_Window, then set HWSTNumber_Low = 0.

Calculate the new value of FHWST_Low.

FHWST_Low = HWSTNumber_Low/(HWST_Too_Low_Window)

2.2.2 Evaluate Hot-Water Temperature Alarm Conditions

Check if the long-term average hot-water supply tempeature (HWST) is adequately maintained or whether it is high or low by comparing FHWST_High and FHWST_Low with thir repective limits.

If FHWST_High >= FHWST_High_Limit,
Set HWST_Maintained_OK/Not = "Too high"

If FHWST_Low >= FHWST_Low_Limit,
Set HWST_Maintained_OK/Not = "Too low"

If FHWST_High < FHWST_HIgh_Limit, AND
FHWST_Low < FHWST_Low_Limit,
Set HWST_Maintained_OK/Not = "OK"

2.2.3 Update Hot Water Temp High Alarm Variables

Update the value of FHWST_High based on the latest value of HWST_Maintained_OK/Not.

Update the HWST_Maintained_OK/not_Too-High_Array

Update all values in the array, adding the current value of HWST_Maintained_OK/not to the array and by dropping the oldest value of HWST_Maintained_OK/not from the array.

Update value for HWSTNumber_High.

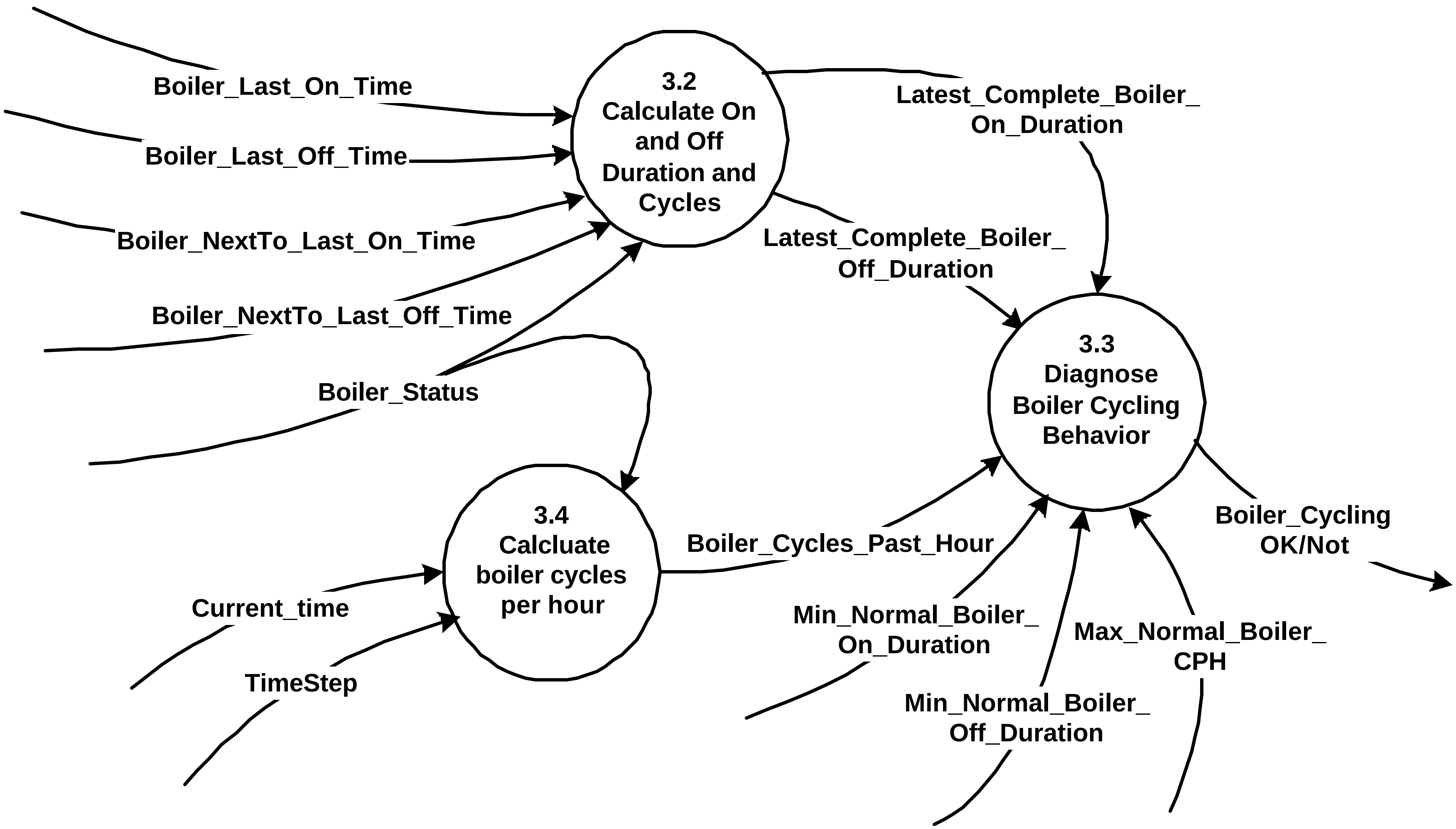
Set HWSTNumber_High = number of values "Too High" appearing in HWST_Maintained_OK/not_Too-High_Array.

If Total Number of Time Steps Processed < HWST_Too_High_Window, then
set HWSTNumber_High = 0.

Calcluate the new value of FHWST_High.

FHWST_High = HWSTNumber_High/(HWST_Too_High_Window)

3.0 Diagnose Boiler Cycling



3.2 Calculate On and Off Duration and Cycles

Calculate Latest_Complete_Boiler_On_Duration

If Boiler_Status = "On"
    Set Latest_Complete_Boiler_On_Duration = Boiler_Last_Off_Time - Boiler_NextTo_Last_On_Time

If Boiler_Status = "Off"
    Set Latest_Complete_Boiler_On_Duration = Boiler_Last_Off_Time - Boiler_Last_On_Time

Calculate Latest_Complete_Boiler_Off_Duration

If Boiler_Status = "Off"
    Set Latest_Complete_Boiler_Off_Duration = Boiler_Last_On_Time - Boiler_NextTo_Last_Off_Time

If Boiler_Status = "On"
    Set Latest_Complete_Boiler_Off_Duration = Boiler_Last_On_Time - Boiler_Last_Off_Time

3.3 Diagnose Boiler Cycling Behavior

If Boiler_Cycles_Past_Hour > Max_Normal_Boiler_CPH, AND Latest_Complete_Boiler_On_Duration < Min_Normal_Boiler_On_Duration AND Latest_Complete_Boiler_Off_Duration < Min_Normal_Boiler_Off_Duration,

then set Boiler_Cycling_OK/Not = "Not OK. The Boiler is cycling on and off excessively."

If Boiler_Cycles_Past_Hour > Max_Normal_Boiler_CPH, AND Latest_Complete_Boiler_On_Duration < Min_Normal_Boiler_On_Duration, AND Latest_Complete_Boiler_Off_Duration >= Min_Normal_Boiler_Off_Duration,

then set Boiler_Cycling_OK/Not = "Not OK. The Boiler is cycling on excessively."

If Boiler Cycles Past Hour > Max_Normal_Boiler_CPH AND Latest_Complete_Boiler_On_Duration >= Min_Normal_Boiler_On_Duration, AND Latest_Complete_Boiler_Off_Duration < Min_Normal_Boiler_Off_Duration,

then set Boiler_Cycling_OK/Not = "Not OK. The Boiler is cycling off excessively."

If Boiler Cycles Past Hour <= Max_Normal_Boiler_CPH,

then set Boiler_Cycling_OK/Not = "OK."

3.4 Calcluate boiler cycles per hour

Set number of time steps in an hours
    Set Nmax = 60/TimeStep

Update Boiler_Status_Array
    Boiler_Status(Current_time - Nmax * TimeStep) = Boiler_Status[Current_time - (Nmax - 1) * TimeStep]
    Boiler_Status[Current_time - (Nmax - 1) * TimeStep] = Boiler_Status[Current_time - (Nmax - 2) * TimeStep]
    •
    •
    •
    Boiler_Status(Current_time - 2 * TimeStep) = Boiler_Status(Current_time - TimeStep)
    Boiler_Status(Current_time - TimeStep) = Boiler_Last_Status
    Boiler_Status(Current_time) = Boiler_Status

Calculate Boiler_Cycles_Past_Hour.
    Assign BSNumber(nt) for all values of nt from -Nmax to 0,
        If Boiler_Status = "On," set BSNumber(nt) = 1.
        If Boiler_Status = "Off," set BSNumber(nt) = 0.

    Set Cycle_Counts = 0

    Evaluate the following for each value of nt for -Nmax <= nt <= 0
    (zero corresponding to the current time and -Nmax corresonding to Nmax time steps ago)

        If Boiler_Status(Current_time) = "Off" AND BSNumber(nt+1) - BSNumber(nt) < 0
        Set Cycle_Counts = Cycle_Counts + 1

        If Boiler_Status(Current_time) = "Off" AND BSNumber(nt+1) - BSNumber(nt) >= 0
        Set Cycle_Counts = Cycle_Counts

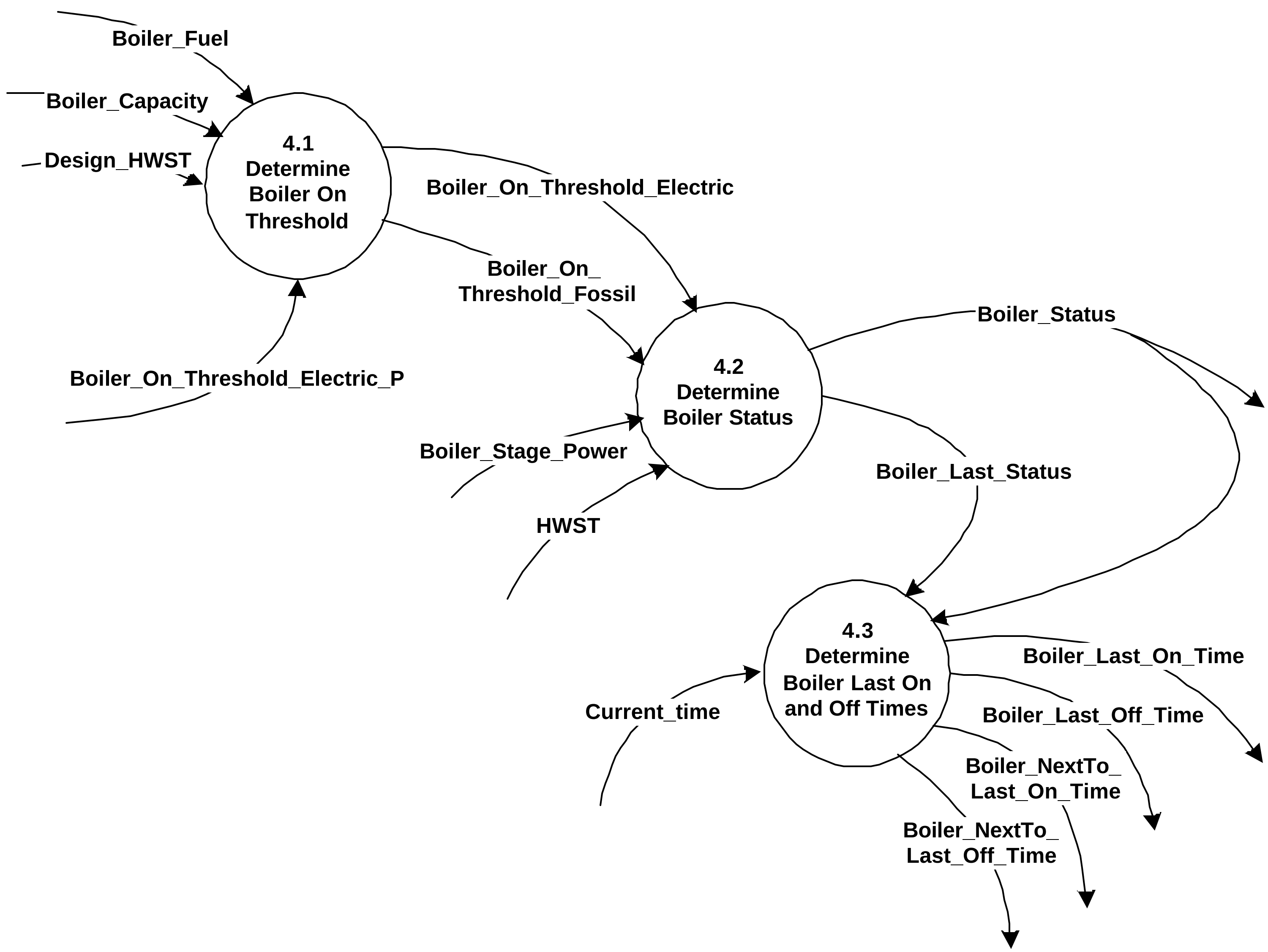
        If Boiler_Status(Current_time) = "On" AND BSNumber(nt+1) - BSNumber(nt) > 0
        Set Cycle_Counts = Cycle_Counts + 1

        If Boiler_Status(Current_time) = "On" AND BSNumber(nt+1) - BSNumber(nt) <= 0
        Set Cycle_Counts = Cycle_Counts

        If nt < 0, repeat for next value of nt.
        If nt = 0, Set Boiler_Cycles_Past_Hour = Cycle_Counts - 1

Note: We can probably specify more efficient ways to update the variables used in this cycle coutning procedure.

4.0 Determine Boiler State



4.1 Determine Boiler On Threshold

Determine the Boiler Type and set corresponding Boiler "On" threshold.

If Boiler_Fuel = Electric, then
    Set Boiler_On_Threshold_Electric = Boiler_On_Threshold_Electric_P * Boiler_Capacity, and
    Set Boiler_On_Threshold_Fossil = null

If the Boiler_Fuel = Fossil, then
    Set Boiler_On_Threshold_Fossil = (Design_HWST + 75)/2, and
    Set Boiler_On_Threshold _Electric = null

4.2 Determine Boiler Status

Update Boiler_Last_Status,

Boiler_Last_Status = Boiler_Status

Check if the boiler on thresholds are exceeded. and set the boiler status accordingly.

If Boiler_Stage_Power > Boiler On Threshold Electric, then
set Boiler_Status = "On"

If HWST > Boiler On Threshold Fossil, then
set Boiler_Status = "On"

Otherwise,

If Boiler_Stage_Power <= Boiler On Threshold Electric,
Set Boiler_Status = "Off"

If HWST <= Boiler On Threshold Fossil,
Set Boiler_Status = "Off"

4.3 Determine Boiler Last On and Off Times

Calculate Boiler_Last_On_Time

If Boiler_Status = "On" and "Boiler_Last_Status = "Off," then
Set Boiler_NextTo_Last_On_Time = Boiler_Last_On_Time
Set Boiler_Last_On_Time = Current_Time

If Boiler_Status = "On" and "Boiler_Last_Status = "On," then
Set Boiler_Last_On_Time = Boiler_Last_On_Time
[Note: No change in value of Boiler_Last_On_Time.]

If Boiler_Status = "Off" and "Boiler_Last_Status = "Off," then
Set Boiler_Last_On_Time = Boiler_Last_On_Time
[Note: No change in value of Boiler_Last_On_Time.]

If Boiler_Status = "Off" and "Boiler_Last_Status = "On," then
Set Boiler_Last_On_Time = Boiler_Last_On_Time
[Note: No change in value of Boiler_Last_On_Time.]

Calculate Boiler_Last_Off_Time

If Boiler_Status = "Off" and "Boiler_Last_Status = "On," then
Set Boiler_NextTo_Last_Off_Time = Boiler_Last_Off_Time
Set Boiler_Last_Off_Time = Current_Time

If Boiler_Status = "Off" and "Boiler_Last_Status = "Off," then
Set Boiler_Last_Off_Time = Boiler_Last_Off_Time
[Note: No change in value of Boiler_Last_Off_Time.]

If Boiler_Status = "On" and "Boiler_Last_Status = "On," then
Set Boiler_Last_Off_Time = Boiler_Last_Off_Time
[Note: No change in value of Boiler_Last_Off_Time.]

If Boiler_Status = "On" and "Boiler_Last_Status = "Off," then
Set Boiler_Last_Off_Time = Boiler_Last_Off_Time
[Note: No change in value of Boiler_Last_Off_Time.]

5.0 Diagnose HW Pump Shutoff

If Boiler_Status = "Off" AND HW_Pump_Status = "Off"
Set HW_Pump_Shutoff_OK/Not = "OK; the hot-water pump is off as it should be."

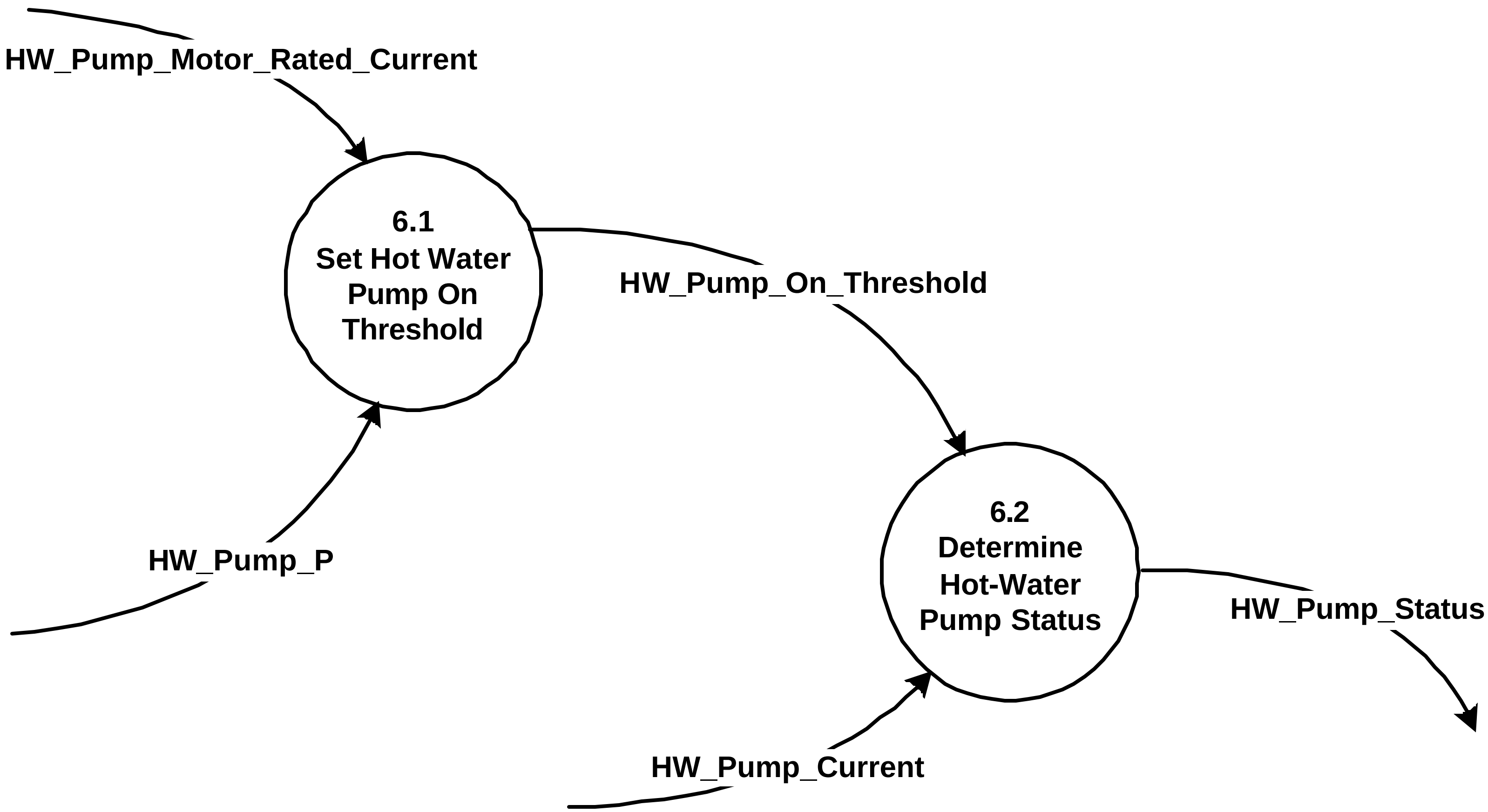
If Boiler_Status = "On" AND HW_Pump_Status = "On"
Set HW_Pump_Shutoff_OK/Not = "OK; the hot-water pump is on while the boiler is on."

If Boiler_Schedule_Type = "Ambient Shutoff" OR "Manual Shutoff" AND
Boiler_Status = "Off" AND
HW_Pump_Status = "On" AND
Current_time - Boiler_Last_On_Time <= HW_Pump_Run_Limit, then
Set HW_Pump_Shutoff_OK/Not = "OK; the hot-water pump is running while the boiler is off, but the hot-water run limit has not been exceeded yet."

If Boiler_Schedule_Type = "Ambient Shutoff" OR "Manual Shutoff" AND
Boiler_Status = "Off" AND
HW_Pump_Status = "On," AND
Current_time - Boiler_Last_On_Time > HW_Pump_Run_Limit, then
Set HW_Pump_Shutoff_OK/Not = "Not OK; the hot-water pump is running unnecessarily, wasting energy, and unnecessarily reducing its remaining operating life."

Note: No diagnostics are provided for HW Pump off while boiler is on. This requires further development. This situation can also present a safety problem so it is important from a safety standpoint as well as efficient operation. Additional diagnostics are needed.

6.0 Determine Hot-Water Pump State



6.1 Set Hot Water Pump On Threshold

Calculate the HW_Pump_On_Threshold using

HW_Pump_On_Threshold = HW_Pump_P x HW_Pump_Motor_Rated_Current

Notes: The value of HW_Pump_P can be a user input or a default value.

6.2 Determine Hot-Water Pump Status

Update HW_Pump_Last_Status

Set HW_Pump_Last_Status = HW_Pump_Status

For each value of HW_Pump_Current, check if the HW_Pump_On_Threshold is exceeded, and set the hot-water pump status accordingly.

If the value of HW_Pump_Current <= HW_Pump_On_Threshold, then
set HW_Pump_Status = "Off"
If the value of HW_Pump_Current > HW_Pump_On_Threshold, then
set HW_Pump_Status = "On."

7. Appendix D: Data Dictionary for Boilers

Variable	Definition	Values
Boiler_Capacity	The cumulative rated capacity of all boilers used for space conditioning in Btu/h.	Capacity in Btu/h
Boiler_Cycles_Past_Hour	A variable that indicates the number of complete boiler on/off cycles that have occurred during the hour immediately preceding the current time.	Positive integer.
Boiler_Cycling OK/Not	Boiler cycling status variable, which can take on values as indicated in the process description.	Ok. "Not OK. The Boiler is cycling on and off excessively." "Not OK. The Boiler is cycling on excessively." "Not OK. The Boiler is cycling off excessively."
Boiler_Fuel	A setup variable that indicates the type of energy source used to fire the boiler.	Electric or Fossil.
Boiler_Last_Off_Time	A variable identifying the absolute time at which the boiler was last shut "Off" (i.e., changed from on to off).	Time in minutes.
Boiler_Last_On_Time	A variable identifying the absolute time at which the boiler was last turned "On" (i.e., changed from off to on).	Time in minutes.
Boiler_Last_Status	The value of the Boiler_Status one time step ago (i.e., the processing time before the current time).	"On" or "Off"
Boiler_NextTo_Last_Off_Time	A variable identifying the absolute at which the boiler was shut "Off" two times ago (i.e., changed from on to off).	Time in minutes.
Boiler_NextTo_Last_On_Time	A variable identifying the absolute time at which the boiler was turned "On" two times ago (i.e., changed from off to on).	Time in minutes.
Boiler_Off_Date	Numeric value for the day of the year on which the boiler is ordinarily turned off at the end of the heating season with the days of the year numbered consecutively; e.g., April 1 is day 91 for a non-leap year.	Numerical value for day of year.

Variable	Definition	Values
Boiler_Off_Date_dDown	The number of days before the Boiler_Off_Date that the boiler may be turned off without the boiler operation considered to be in error (i.e., it should be on).	Number of days
Boiler_Off_Date_dUp	The number of days beyond the Boiler_Off_Date that the boiler may be on before the boiler operation is considered to be in error (i.e., it should be off).	Number of days
Boiler_On_Date	Numeric value for the day of the year on which the boiler is normally turned on for the heating season with the days of the year numbered consecutively; e.g., October 31 is day 304 for a non-leap year.	Numerical value for day of year.
Boiler_On_Date_dDown	The number of days before the Boiler_On_Date that the boiler may be turned on without the boiler operation considered to be in error (i.e., it should be off).	Number of days
Boiler_On_Date_dUp	The number of days beyond the Boiler_On_Date that the boiler may be off before the boiler operation is considered to be in error (i.e., it should be on).	Number of days
Boiler_On_Threshold_Electric	The electric current threshold above which an electric boiler is considered “On.”	Electric current in amps or null. Real.
Boiler_On_Threshold_Electric_P	Fraction of Boiler_Capaciity selected for the "On" Threshold for electric boilers (e.g. 0.01)	Dimensionless real number between 0.0 and 1.0 (e.g., 0.01)
Boiler_On_Threshold_Fossil	The hot water supply temperature above which a fossil fuel-fired boiler is considered “On.”	Temperature in degrees F or null. Real.
Boiler_Schedule_Type	An indicator of the type of boiler schedule. It can take values of “Ambient Shutoff,” “Manual Shutoff,” and “Always On.”	“Ambient Shutoff,” “Manual Shutoff,” or “Always On.”

Variable	Definition	Values
Boiler_Shutoff_OK/Not	A variable that indicates whether shut off of the boiler is controlled properly for and consistently with the type of boiler.	"OK. The boiler is on as it should be. Shutoff is not applicable to this boiler. The boiler system is designed for continuous operation." "Not OK; the boiler is off and it should be on always, unless it is locked out temporarily for maintenance or repair." "OK; the boiler is on as it should be." "OK; the boiler is off as it should be" "Not OK; the boiler is off when it should be on." "Not OK; the boiler is on when it should be off." "Ok; the date is too close to the Boiler On Date to evaluate compliance with the schedule." "Ok; the date is too close to the Boiler Off Date to evaluate compliance with the schedule."
Boiler_Stage_Power	The electric power to the boiler heating elements at the current time. Does not include auxiliary power such as valves and fans.	Electric power in watts. Real.
Boiler_Status	A variable indicating whether the boiler is on or off.	On or Off.
Boiler_Status(nt * TimeStep)	Boiler_Status at the time (nt * TimeStep). The variable nt takes values less than or equal to zero.	On or Off.
BSNumber	A numerical indicator of the Boiler_Status, where Boiler_Status = “on” corresponds to BSNumber = 1, and Boiler_Status = “Off” corresponds to BSNumber = 0.	0 or 1
Current_Date	A numerical indicator of the current date corresponding to the current processing time, counting from January 1 of each year.	Date
Current_Time	The absolute time of the current time step.	Time in minutes.

Variable	Definition	Values
Cycle_Counts	An local variable used to keep count of the number of complete on/off cycles during a designated time period.	Integer values.
Design_HWST	Design hot-water supply temperature.	Temperature in degrees F. Real.
FHWST_High	Fraction of HWST-SP_Maintained_OK/Not equal to "Too High" over the last HWST_Too_High_Window	Real value between 0.0 and 1.0.
FHWST_High_Limit	The fraction of "Too High" hot water supply temperature observations over the designated time window for which the long-term HWST is judged too high.	Real value between 0.0 and 1.0.
FHWST_Low	Fraction of HWST-SP_Maintained_OK/Not equal to "Too Low" over the last HWST_Too_Low_Window.	Real value between 0.0 and 1.0.
FHWST_Low_Limit	The fraction of "Too Low" hot water supply temperature observations over the designated time window for which the long-term HWST is judged too low.	Real value between 0.0 and 1.0.
HW_Pump_Current	The measured value of current for the hot-water pump	Current in amps.
HW_Pump_On_Threshold	The value of hot-water pump current (HW_Pump_Current) above which the pump is considered on.	Current in amps.
HW_Pump_Last_Status	The value of the HW_Pump_Status one time step ago (i.e., the processing time before the current time).	"On" or "Off"
HW_Pump_Motor_Rated_Current	Current rating of the hot-water pump motor from the motor nameplate.	Current in amps.
HW_Pump_P	Fraction of Hot-Water pump rated current selected for the "On" Threshold.	Dimensionless real number between 0.0 and 1.0.
HW_Pump_Run_Limit	The maximum time interval after the boiler turns off during which the hot-water pump can run. After this time, the hot-water pump should not turn on again until the boiler turns on.	Time interval in hours.

Variable	Definition	Values
HW_Pump_Shutoff_OK/Not	A variable indicator whether the On/Off status of the hot-water pump is being controlled properly or not, and if not, how is it's control wrong.	"OK; the hot-water pump is off as it should be." "OK; the hot water pump is on while the boiler is on." "Hot Water Pumping Fault; the pump is off too much while the boiler is on." "HW Pump is running unnecessarily and wasting energy and useful operating life." "OK; the hot-water pump is running while the boiler is off, but the hot-water run limit has not been exceeded yet."
HW_Pump_Status	A variable indicating whether the hot-water pump is on or off.	"On" or "Off"
HWST	Hot-water supply temperature	Temperature in degrees F.
HWST_dDown	Maximum acceptable deviation of the hot-water supply temperature below its set point for a single measurement.	Temperature in degrees F.
HWST_Deviation	The hot water supply temperature deviation from set point for the current observation. [Note: This output is included only for consistency with the chilled water reset diagnostic and may not be needed.]	Temperature difference in degrees F.
HWST_dUp	Maximum acceptable deviation of the hot-water supply temperature above its setpoint for a single measurement.	Temperature in degrees F.
HWST_Maintained_OK/Not	Hot Water Supply Temperature Status Message. Possible values: "OK," "Too high," "Too Low."	Ok. Too high. Too low.

Variable	Definition	Values
HWST_Maintained_OK/not_Too-Low_ Array	The array: {HWST_Maintained_OK/not, HWST_Maintained_OK/not (1 time step ago), HWST_Maintained OK/not (2 time steps ago), HWSTMaintained_OK/not (3 time steps ago), HWST_Maintained-OK/not (4 time steps ago), ...HWST_Maintained_OK/not [(HWST_Too_Low_Window – 1) time steps ago]}	Array with individual elements takings values of Ok, Too High, or Too Low.
HWST_Maintained_OK/not_Too-High_ Array	The array: {HWST_Maintained_OK/not, HWST_Maintained_OK/not (1 time step ago), HWST_Maintained OK/not (2 time steps ago), HWSTMaintained_OK/not (3 time steps ago), HWST_Maintained-OK/not (4 time steps ago), .HWST_Maintained_OK/not [(HWST_Too_High_Window – 1) time steps ago]}	Array with individual elements takings values of Ok, Too High, or Too Low.
HWSTNumber_High	HWSTNumber High is the number of values of the variable HWST_Maintained_OK/not with values of “Too High” during the last HWST_Too_High_Window time steps.	Integer.
HWSTNumber_Low	HWSTNumber Low is the number of values of the variable HWST_Maintained_OK/not with values of “Too Low” during the last HWST_Too_Low_Window time steps.	Integer.
HWST_Setpoint-Current	Hot-water supply temperature setpoint for the current time.	Temperature in degrees F.
HWST-SP_Maintained_OK/Not	An indicator of whether the hot-water supply temperature is adequately maintained at a single point in time.	OK Too high Too low
HWST_Too_High_Window	Length in number of observations of the moving time window over which the percentage of too high hot water supply temperatures is evaluated.	Number of time steps. Integer
HWST_Too_Low_Window	Length in number of observations of the moving time window over which the percentage of too low hot water supply temperatures is evaluated.	Number of time steps. Integer

Variable	Definition	Values
Latest_Complete_Boiler_Off_Duration	The length of time over which the boiler was off the last time it went through a complete off-cycle (i.e., from on to off to on again).	Time interval in minutes.
Latest_Complete_Boiler_On_Duration	The length of time over which the boiler was on the last time it went through a complete on-cycle (i.e., from off to on to off again).	Time interval in minutes.
Max_Normal_Boiler_CPH	A setup variable for the maximum number of cycles that the boiler should go through in an hour.	Positive integer.
Min_Normal_Boiler_Off_Duration	A setup variable that indicates the minimum time the boiler should be off before turning on again.	Time interval in minutes.
Min_Normal_Boiler_On_Duration	A setup variable that indicates the minimum time the boiler should be on before shutting off again.	Time interval in minutes.
Nmax	Number of times steps per hour = 60/TimeStep = the rounded number of calculation time steps per hour given the length of the time step designated during set up.	Positive integer.
nt	An index for the number of time steps.	Integer, usually less than or equal to zero.
TimeStep	A setup variable for the length of time between successive processings in minutes (which is assumed constant).	Time increment in minutes.
Time_Steps_Processed	Total number of time steps processed since the beginning of processing.	Integer.

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Project 2.5 – Pattern-Recognition Based Fault Detection and Diagnostics

Deliverable 2.5.6b

Evaluation of Energy Impact of Faults

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1.0 Introduction

Detecting HVAC system faults alerts operators of potential problems, and allows them to take appropriate action to resolve the system fault. Addressing the cause of the fault can be relatively low cost as in the case of a simple control change to restore proper schedules. However, elimination of other faults can be relatively expensive, especially those requiring substantial hardware replacements. An economic analysis would suggest that before repairing the fault, the cost of not repairing the fault would have to be greater than repairing the fault. The purpose of this activity is to evaluate the energy impacts of faults that are detected by the Project 2.5 Fault Detection software.

2.0 Analysis Methodology

The faults that are to be detected by the Fault Detection Software have been outlined in "Project 2.5 – Pattern-Recognition Based Fault Detection and Diagnostics; Automated Diagnostics Software Requirements Specification, July 2002." These faults are reproduced in Table 1 below.

Table 1. Faults

Subsystem	Monitored Parameter	Fault Category	Fault
Chiller	Chilled Water Supply Temperature Maintenance	Chilled Water Supply Temperature not Maintained Correctly	The chilled water supply temperature is too high
			The chilled water supply temperature is too low
	Chiller Schedule	Chiller Schedule is Incorrect/in Error/Corrupt/Inefficient/not Followed	The chiller is on when it should be off. Energy is being wasted.
	Compressor Cycling	Compressor Cycling is Abnormal	The compressor is cycling on too frequently. It is not staying off for the minimum required off time.
			The compressor is cycling off too frequently. It is not staying on for the minimum required on time.
	Compressor and Condenser Fan Interlock (for air-cooled condensers only)	Compressor is Improperly Interlocked with Condenser Fan	The compressor is on while the condenser fan is off. The chiller cannot reject heat and this could damage the compressor
			The condenser fan is on while the compressor is off. The fan is running unnecessarily and wasting energy.
	Compressor and Condenser Pump Interlock (for water-cooled condensers only)	Compressor is Improperly Interlocked with Condenser Pump	The compressor is on while the condenser pump is off. The chiller cannot reject heat and this could damage the compressor.
			The condenser pump is cycling unnecessarily frequently. Repeated frequent cycling will shorten the life of the condenser pump.
			The condenser pump is turning on too much in advance of the compressor and wasting energy.
Cooling Tower	Cooling Tower Fan Cycling	Cooling Tower Fan Cycling Problem	The cooling tower fan is not staying off long enough during cycling.
			The cooling tower fan is not staying on long enough during cycling.

Subsystem	Monitored Parameter	Fault Category	Fault
	Sump Temperature Control	Sump Temperature is Improperly Controlled	The cooling tower fan is off but should be on. As a result, the condenser water is not being cooled sufficiently.
			The cooling tower fan is on but it should be off. Energy is being wasted.
	Cooling Tower Approach	Cooling Tower Approach Problem	The cooling tower approach is greater than the Approach Benchmark provided in set up. Heat rejection from the cooling tower is less than expected.
	Cooling Tower Fan Staging	Cooling Tower Fan Staging Problem	The Sump temperature is above the cooling tower fan "on" set point, but all cooling tower fans are not on. This indicates a problem with the fan staging and, as a result, the cooling tower is not maintaining the sump temperature as low as it should.
			A fan is on even though the sump temperature is below the "off" set point. This indicates a fan staging problem, and energy is being wasted. All cooling tower fans should be off.
	Cooling Tower Range	Cooling Tower Range Problem	The cooling tower range is below its benchmark. As result, heat rejection by the cooling tower is less than expected and the cooling tower is performing at less than its capacity.
Chilled Water Loop	Supply Fan(s) and the Primary-Loop Chilled Water Pumps Interlock	Supply Fan(s) and the Primary-Loop Chilled Water Pumps are not Interlocked Properly	The is possibly a problem with the supply fan control.
			This chilled water pump is being operated unnecessarily and is wasting energy. The chilled water pump should not operate unless at least one of the supply fans in an air handling unit served by the chilled water pump is on.
	Supply Fan(s) and the Secondary-Loop Chilled Water Pumps Interlocked	Supply Fan(s) and the Secondary-Loop Chilled Water Pumps are not Interlocked Properly.	Possible problem with secondary chilled water pump control—check to see if loads in the spaces served are being met for all supply fans that are part of air handlers served by this secondary chilled water loop and that is on when the secondary chilled water pump is off.
			The secondary chilled water pump and some of the supply fans that are served by it are not interlocked properly. This secondary chilled water pump is operating unnecessarily when all supply plans it serves are off and, as a result, is wasting energy. The secondary chilled water pump should not operate unless at least one of the supply fans in an air handler served by this pump is on.
	Secondary and Primary Loop Chilled Water Pumps Interlock	Secondary and Primary Loop Chilled Water Pumps are not Interlocked Properly	The secondary chilled water pumps that are on are wasting energy. Secondary chilled water pumps should only operate when the primary CHW pump is operating.
Chiller / Cooling Tower	Cooling Tower Fan(s) and Condenser Pump Interlock	Cooling Tower Fan(s) and Condenser Pump are not Interlocked Properly	The cooling tower fan and condenser pump are not interlocked properly. Energy is being wasted because the cooling tower fan should be off when the condenser pump is not operating.
			The interlock between the condenser pump and the cooling tower may not be properly implemented. The cooling tower fan may be off when the condenser pump is running, but this should not always be the case.

Subsystem	Monitored Parameter	Fault Category	Fault
Chiller / Water Loop	Compressor and Primary Chilled Water Pump(s) Interlock	Compressor and Primary Chilled Water Pump(s) are not Interlocked Properly	The primary chilled water pumps are not interlocked properly with the compressor. The condenser pump is cycling on and off unnecessarily. Repeated frequent cycling will shorten the life of the pump.
			The compressor is not properly interlocked with the primary chilled water pumps. The chiller is operating without a load. Energy is being wasted and damage to the compressor may result.
			The compressor is not properly interlocked with the primary chilled water pumps. Water side economizing is not being used, and the primary chilled water pumps are cycling on too much in advance of the compressor and wasting energy.

The faults in Table 1 were reviewed to determine the following:

- Type of fault (time-based, schedule-based, temperature, cycling, etc.)
- Methods that could be used to calculate energy impact. The expected methods include DOE-2 simulations or simple algorithms.

The results of this review are shown in Table 2. The last column indicates if the impact of the fault will be analyzed, and the method that will be used for the analysis. In general, the faults fall into the following categories:

1. Schedule-based faults
2. Temperature-based faults
3. Cycling-based faults
4. Faults that do not have a significant energy impact, but do have an impact on equipment life.

Some of the faults listed in Table 2 do not, by themselves, have an energy impact. Some are better characterized as "diagnostic conditions." For example, the cooling tower approach, which is the difference between the sump temperature and the wet bulb temperature, will often be greater than the approach "benchmark," especially during low load or low ambient conditions. However, if the sump temperature is greater than the set point, then there will be an energy impact. The cooling tower approach, along with other variables, would be evaluated under these conditions to determine WHY the sump temperature is high.

Table 2. Fault Review

Sub-system	Monitored Parameter	Fault Category	Fault	Calculate Impact?	Fault ID
Chiller	Chilled Water Supply Temperature Maintenance	Chilled Water Supply Temperature not Maintained Correctly	The chilled water supply temperature is too high	Yes.	C-1
			The chilled water supply temperature is too low	Yes.	C-2

Sub-system	Monitored Parameter	Fault Category	Fault	Calculate Impact?	Fault ID
	Chiller Schedule	Chiller Schedule is Incorrect/in Error/Corrupt/Inefficient/not Followed	The chiller is on when it should be off. Energy is being wasted.	Yes.	C-3
	Compressor Cycling	Compressor Cycling is Abnormal	The compressor is cycling on too frequently. It is not staying off for the minimum required off time.	No. Cycling cannot be modeled	C-4
			The compressor is cycling off too frequently. It is not staying on for the minimum required on time.	No. Cycling cannot be modeled	C-5
	Compressor and Condenser Fan Interlock (for air-cooled condensers only)	Compressor is Improperly Interlocked with Condenser Fan	The compressor is on while the condenser fan is off. The chiller cannot reject heat and this could damage the compressor	No. Impacts equipment life, but has minimal energy impact.	C-6
			The condenser fan is on while the compressor is off. The fan is running unnecessarily and wasting energy.	Yes.	C-7
	Compressor and Condenser Pump Interlock (for water-cooled condensers only)	Compressor is Improperly Interlocked with Condenser Pump	The compressor is on while the condenser pump is off. The chiller cannot reject heat and this could damage the compressor.	No. Impacts equipment life, but has minimal energy impact.	C-8
			The condenser pump is cycling unnecessarily frequently. Repeated frequent cycling will shorten the life of the condenser pump.	No. Cycling cannot be modeled	C-9
			The condenser pump is turning on too much in advance of the compressor and wasting energy.	Yes.	C-10
Cooling Tower	Cooling Tower Fan Cycling	Cooling Tower Fan Cycling Problem	The cooling tower fan is not staying off long enough during cycling.	No. Cycling cannot be modeled	CT-1
			The cooling tower fan is not staying on long enough during cycling.	No. Cycling cannot be modeled	CT-2
	Sump Temperature Control	Sump Temperature is Improperly Controlled	The cooling tower fan is off but should be on. As a result, the condenser water is not being cooled sufficiently.	Yes.	CT-3
			The cooling tower fan is on but it should be off. Energy is being wasted.	Yes	CT-4

Sub-system	Monitored Parameter	Fault Category	Fault	Calculate Impact?	Fault ID
	Cooling Tower Approach	Cooling Tower Approach Problem	The cooling tower approach is greater than the Approach Benchmark provided in set up. Heat rejection from the cooling tower is less than expected.	No. Approach will be greater than benchmark except during design conditions. This is a diagnostic that POINTS to a probable reduction in cooling tower capacity. Reduced cooling tower capacity is a major problem during high ambient conditions, but is a minor problem during low ambient conditions. During high ambient conditions, reduced CT capacity will cause higher than desired approach, which in turn will cause increased sump temperature, resulting in increased chiller electrical consumption.	CT-5
	Cooling Tower Fan Staging	Cooling Tower Fan Staging Problem	The Sump temperature is above the cooling tower fan “on” set point, but all cooling tower fans are not on. This indicates a problem with the fan staging and, as a result, the cooling tower is not maintaining the sump temperature as low as it should.	Yes.	CT-6
			A fan is on even though the sump temperature is below the “off” set point. This indicates a fan staging problem, and energy is being wasted. All cooling tower fans should be off.	Yes.	CT-7
	Cooling Tower Range	Cooling Tower Range Problem	The cooling tower range is below its benchmark. As result, heat rejection by the cooling tower is less than expected and the cooling tower is performing at less than its capacity.	No. Range will be less than benchmark except during high load conditions. The range will always be sufficient to reject all heat from the chiller. Because of this reason, this fault detection may not be useful for cooling tower diagnostics. Better to look at sump temperature first, and then if sump temperature is high, examine cooling tower fan operation and cooling tower approach.	CT-8
Chilled Water Loop	Supply Fan(s) and the Primary-Loop Chilled Water Pumps Interlock	Supply Fan(s) and the Primary-Loop Chilled Water Pumps are not Interlocked Properly	There is possibly a problem with the supply fan control.		

Sub-system	Monitored Parameter	Fault Category	Fault	Calculate Impact?	Fault ID
			This chilled water pump is being operated unnecessarily and is wasting energy. The chilled water pump should not operate unless at least one of the supply fans in an air handling unit served by the chilled water pump is on.	Yes.	ChWL-1
	Supply Fan(s) and the Secondary-Loop Chilled Water Pumps Interlocked	Supply Fan(s) and the Secondary-Loop Chilled Water Pumps are not Interlocked Properly.	Possible problem with secondary chilled water pump control—check to see if loads in the spaces served are being met for all supply fans that are part of air handlers served by this secondary chilled water loop and that is on when the secondary chilled water pump is off.	Yes.	ChWL-2
			The secondary chilled water pump and some of the supply fans that are served by it are not interlocked properly. This secondary chilled water pump is operating unnecessarily when all supply plans it serves are off and, as a result, is wasting energy. The secondary chilled water pump should not operate unless at least one of the supply fans in an air handler served by this pump is on.	Yes.	ChWL-3
	Secondary and Primary Loop Chilled Water Pumps Interlock	Secondary and Primary Loop Chilled Water Pumps are not Interlocked Properly	The secondary chilled water pumps that are on are wasting energy. Secondary chilled water pumps should only operate when the primary CHW pump is operating.	Yes.	ChWL-4
Chiller / Cooling Tower	Cooling Tower Fan(s) and Condenser Pump Interlock	Cooling Tower Fan(s) and Condenser Pump are not Interlocked Properly	The cooling tower fan and condenser pump are not interlocked properly. Energy is being wasted because the cooling tower fan should be off when the condenser pump is not operating.	Yes.	ChWL-5
			The interlock between the condenser pump and the cooling tower may not be properly implemented. The cooling tower fan may be off when the condenser pump is running, but this should not always be the case.	No. Determining if the fan is not running when it should, is better handled by sump temperature control diagnostics. Determination of this impact is discussed elsewhere.	ChWL-6

Sub-system	Monitored Parameter	Fault Category	Fault	Calculate Impact?	Fault ID
Chiller / Water Loop	Compressor and Primary Chilled Water Pump(s) Interlock	Compressor and Primary Chilled Water Pump(s) are not Interlocked Properly	The primary chilled water pumps are not interlocked properly with the compressor. The chilled water pump is cycling on and off unnecessarily. Repeated frequent cycling will shorten the life of the pump.	No. Cycling cannot be modeled	ChWL-7
			The compressor is not properly interlocked with the primary chilled water pumps. The chiller is operating without a load. Energy is being wasted and damage to the compressor may result.	No. Cycling cannot be modeled	ChWL-8
			The compressor is not properly interlocked with the primary chilled water pumps. Water side economizing is not being used, and the primary chilled water pumps are cycling on too much in advance of the compressor and wasting energy.	Yes.	ChWL-9

The impact of schedule-based faults can be evaluated through simple algorithms, while temperature-based faults require a simulation-based approach due to their interactive effects. The energy impacts of cycling-based faults and faults that have an impact on equipment life are difficult to assess through modeling or other techniques. The energy impacts of these faults will not be evaluated. A list of each fault and the calculation method is shown in Table 3 below.

Table 3. Impact Calculation Methodology Summary

#	Simulation, Algorithm, or None	Fault	Comments
C-1	DOE-2 Simulation	The chilled water supply temperature is too high	Impacts: Chiller and Cooling Tower energy consumption
C-2	DOE-2 Simulation	The chilled water supply temperature is too low	Impacts: Chiller and Cooling Tower energy consumption
C-3	Algorithm	The chiller is on when it should be off. Energy is being wasted.	Wasted chiller energy will be calculated for the time it was detected to be running unnecessarily.
C-7	Algorithm	The condenser fan is on while the compressor is off. The fan is running unnecessarily and wasting energy.	Wasted condenser fan energy will be calculated for the time it was detected to be running unnecessarily
C-10	Algorithm	The condenser pump is turning on too much in advance of the compressor and wasting energy.	Wasted condenser pump energy will be calculated for the time it was detected to be running unnecessarily
CT-3	DOE-2 Simulation	The cooling tower fan is off but should be on. As a result, the condenser water is not being cooled sufficiently.	The IMPACT of improper sump temperature control will be simulated. There could be several CAUSES for improper sump temperature control, including CT fan being off or deteriorated capacity. Deteriorated capacity may be characterized by high approach temperatures at design conditions.

#	Simulation, Algorithm, or None	Fault	Comments
CT-4	DOE-2 Simulation	The cooling tower fan is on but it should be off. Energy is being wasted.	Yes The sump temperature is lower than the set point, and the fan is running unnecessarily.
CT-6	DOE-2 Simulation	The Sump temperature is above the cooling tower fan “on” set point, but all cooling tower fans are not on. This indicates a problem with the fan staging and, as a result, the cooling tower is not maintaining the sump temperature as low as it should.	Yes. Impact of increased sump temperature will be evaluated.
CT-7	DOE-2 Simulation	A fan is on even though the sump temperature is below the “off” set point. This indicates a fan staging problem, and energy is being wasted. All cooling tower fans should be off.	Yes. Impact of decreased sump temperature will be evaluated. Impact of fans running when they should be off will be evaluated for the period that they were detected.
ChWL-1	Algorithm	This chilled water pump is being operated unnecessarily and is wasting energy. The chilled water pump should not operate unless at least one of the supply fans in an air handling unit served by the chilled water pump is on.	Primary CHW pump energy will be calculated for the time it was detected to be running unnecessarily.
ChWL-2	Algorithm	Possible problem with secondary chilled water pump control—check to see if loads in the spaces served are being met for all supply fans that are part of air handlers served by this secondary chilled water loop and that is on when the secondary chilled water pump is off.	Secondary CHW pump energy will be calculated for the time it was detected to be running unnecessarily. However, if supply air temperature is cool enough, it is acceptable for supply fan to operate without secondary CHW pump.
ChWL-3	Algorithm	The secondary chilled water pump and some of the supply fans that are served by it are not interlocked properly. This secondary chilled water pump is operating unnecessarily when all supply plans it serves are off and, as a result, is wasting energy. The secondary chilled water pump should not operate unless at least one of the supply fans in an air handler served by this pump is on.	Secondary CHW pump energy will be calculated for the time it was detected to be running unnecessarily.
ChWL-4	Algorithm	The secondary chilled water pumps that are on are wasting energy. Secondary chilled water pumps should only operate when the primary CHW pump is operating.	Secondary CHW pump energy will be calculated for the time it was detected to be running unnecessarily.
ChWL-5	None	The cooling tower fan and condenser pump are not interlocked properly. Energy is being wasted because the cooling tower fan should be off when the condenser pump is not operating.	Cooling tower fan energy will be calculated for the time it was detected to be running unnecessarily.

#	Simulation, Algorithm, or None	Fault	Comments
ChWL-9	Algorithm	The compressor is not properly interlocked with the primary chilled water pumps. Water side economizing is not being used, and the primary chilled water pumps are cycling on too much in advance of the compressor and wasting energy.	Primary CHW pump energy will be calculated for the time it was detected to be running unnecessarily.

3.0 Results

3.1 Simulation-based evaluation

A subset of building models from the California Statewide Building Efficiency Assessment (BEA) Study were selected to evaluate the effects of various operational changes. The following steps summarize the general procedure:

- Run base case to allow systems to self-size properly.
- Freeze capacities of all equipment.
- Change the selected parameter, e.g., chilled water supply temperature set point.
- Run model and extract monthly results.
- Normalize monthly results. The monthly results were normalized as shown below:

$$\text{Impact Factor (kWh/kWh - F)} = \frac{\text{Modified kWh - Baseline kWh}}{\text{Baseline kWh * Temp deviation(F)}}$$

The above procedure was applied to the building set, covering all of the California climate zones. The results have been plotted in the following figures as a function of monthly wet bulb temperature, which was a good indicator of load.

3.1.1 Chilled Water Supply Temperature Deviation

The chilled water supply temperature was varied above and below the baseline set point 1°F, 3°F, and 5°F. The impact factor is nearly constant at about 1.3 percent, as shown in Figure 1 and Figure 2.

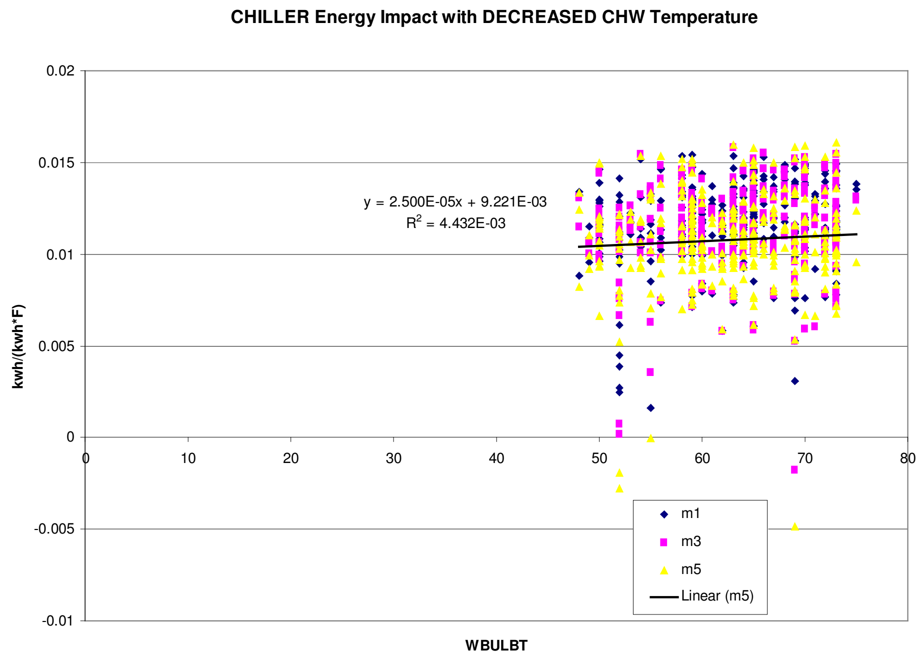

Figure 1. Monthly chiller energy impact with decreased chilled water temperature

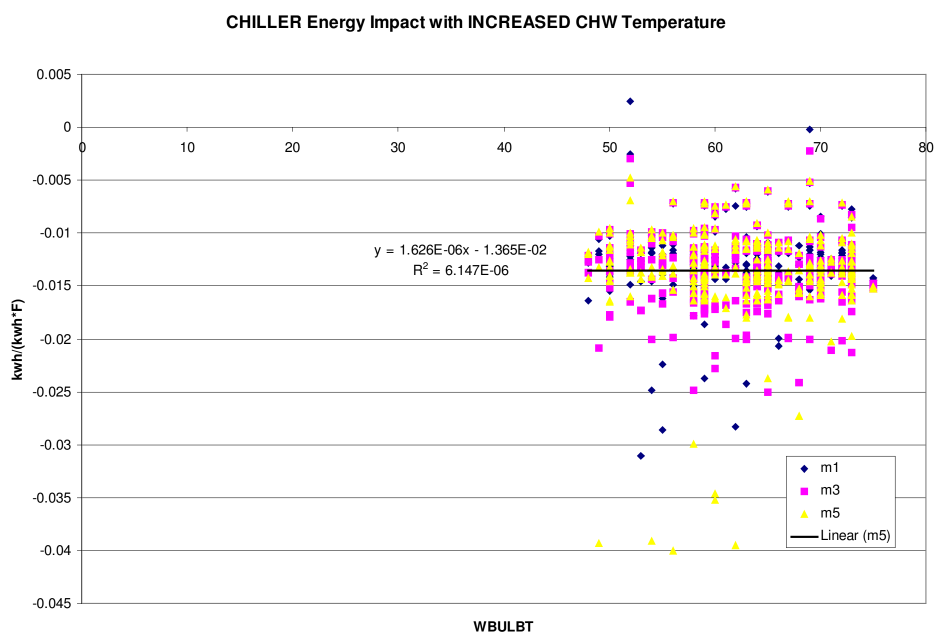

Figure 2. Monthly chiller energy impact with increased chilled water temperature

3.1.2 Cooling Tower Sump Temperature Deviation

To evaluate the effect of changes in the sump temperature on the chiller and cooling tower energy consumption, the cooling tower sump temperature set point was changed in the simulation models. The subsequent change in energy consumption provides an estimate of how changes in the cooling tower sump temperature will affect cooling energy consumption throughout the year.

In general, reducing the sump temperature set point reduces chiller energy consumption, but increases cooling tower fan energy. The effects are greatest at low wet bulb temperatures, and smallest at high wet bulb temperatures. The reason for this is that at low wet bulb temperatures, the cooling tower normally has excess capacity, and it is possible to reduce the sump temperature. Decreasing the sump temperature set point will increase the cooling tower fan operation, which will subsequently reduce the sump temperature and decrease the chiller energy consumption.

At higher wet bulb temperatures, the effects are not as pronounced. The reason for this is that there is less cooling tower capacity available to decrease the sump temperature because the cooling tower fans are already operating at a higher duty cycle. Decreasing the sump temperature set point will further increase the fan operation, but the percentage increase is not as great. Furthermore, the actual sump temperature may not reach the set point since the increased ambient wet bulb temperature may be too high, even at the minimum approach delta temperature.

As the temperature entering the chiller condenser decreases, the energy consumption of the chiller decreases. The impact factor is somewhat correlated with the monthly average wet bulb temperature, as shown in Figure 3 through Figure 6. The results are summarized in Table 4.

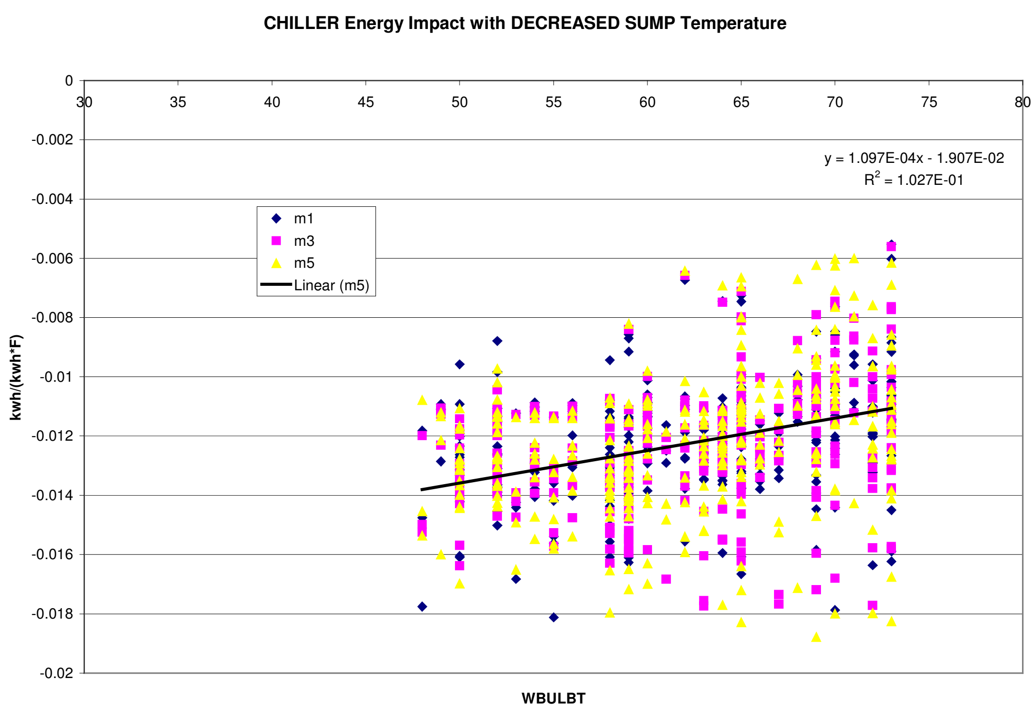

Figure 3. Monthly chiller energy impact with decreased cooling tower sump temperature

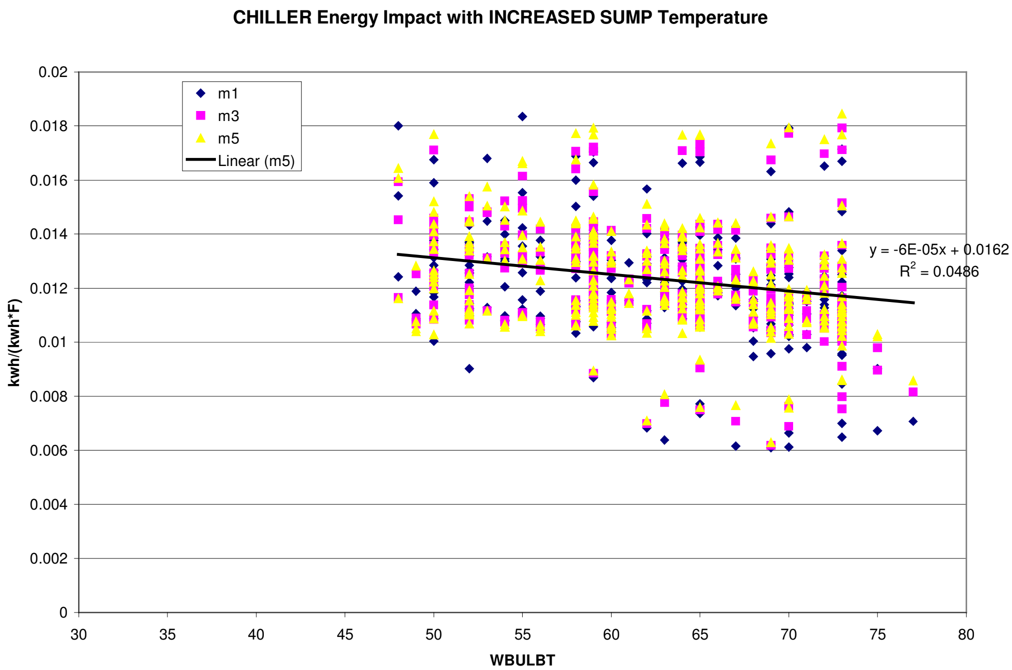

Figure 4. Monthly chiller energy impact with increased cooling tower sump temperature

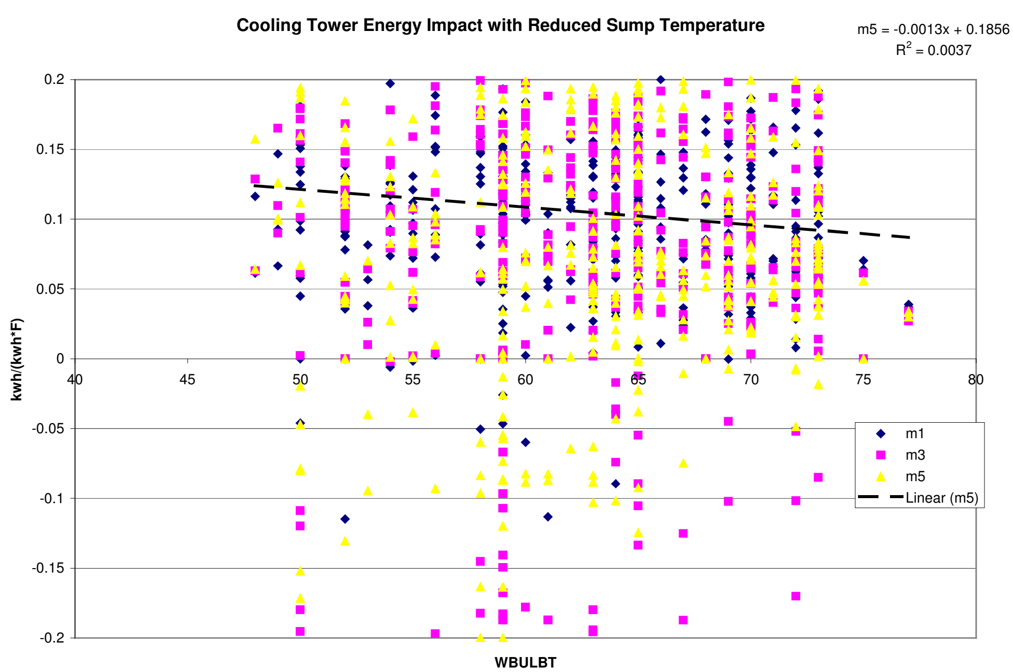

Figure 5. Monthly cooling tower fan energy impact with decreased cooling tower sump temperature

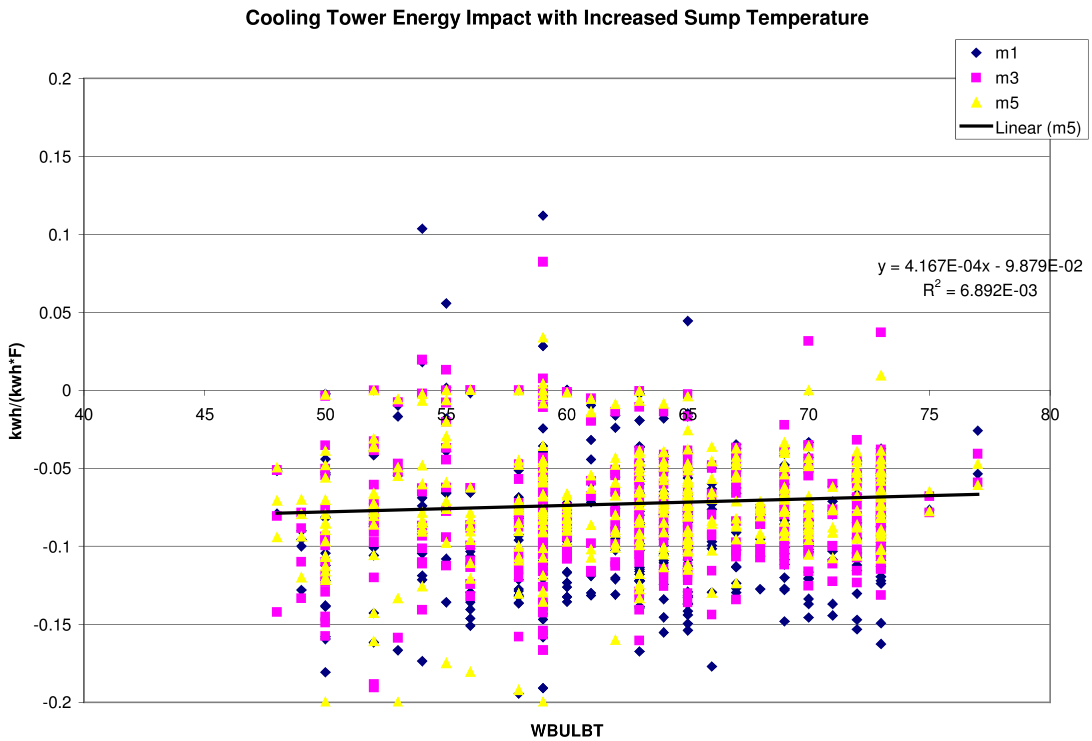

Figure 6. Monthly cooling tower fan energy impact with increased cooling tower sump temperature

Table 4. Summary of Simulation-based Impact Factors

Fault ID	Description	End Use	Slope	Constant
C-1*	CHW Supply Temperature Greater than set point	Chiller	0	-0.0132
C-2*	CHW Supply Temperature Less than set point	Chiller	0	0.0113
CT-4	Cooling Tower Sump Temperature less than set point	Chiller	.000110	-.0191
		Cooling Tower Fan	-0.0013	0.186
CT-3	Cooling Tower Sump Temperature greater than set point	Chiller	-.0000617	.0162
		Cooling Tower Fan	.000417	- .0988

*Cooling Tower energy consumption impact was negligible

3.1.3 Using the simulation results to calculate energy impact

The impacts in the previous section, summarized in Table 4, can be used to calculate energy impacts using a minimum number of variables. As shown in the table, energy impacts can be calculated for chilled water supply temperature greater or less than the set point, and Cooling Tower sump temperature greater or less than the set point. As shown in the figures in the preceding section, the effect on energy consumption is weakly correlated with the ambient wet bulb temperature.

To apply these impacts, the following inputs are required:

- Energy consumption for the period that the temperature deviated from set point.
- Magnitude of temperature deviation, i.e., the difference between the observed and desired temperature for either the chilled water supply temperature or the cooling tower sump temperature.
- Ambient wet bulb temperature for the period being evaluated.

The evaluation period should be no less than one day, and no more than one month.

For calculating a daily impact, the procedure is as follows

1. Select the applicable Fault ID
2. If necessary, determine the daily average wet bulb temperature.
3. Determine the magnitude of the temperature deviation
4. Determine the daily energy consumption of the end use.
5. Calculate the energy impact using the following formulas.

$$E_{Impact} = E_{measured} * F * DT$$

$$Where:$$

$$E_{Impact} = Energy\ consumption\ impact\ (kWh)$$

$$E_{measured} = Measured\ energy\ consumption\ for\ period\ (kWh)$$

$$F = Impact\ Factor = Constant * Slope * T_{WB}$$

$$Constant\ from\ Table\ 4$$

$$Slope\ from\ Table\ 4$$

$$T_{WB} = Wet\ Bulb\ Temperature\ for\ the\ period\ under\ consideration, i.e., day, week, month\ (°F)$$

$$DT = Deviation\ between\ desired\ and\ observed\ temperature\ (°F)$$

3.2 Algorithm-based results

Nearly all of the algorithm-based results are associated with components or systems that are operating longer than is required. The general form of the algorithm is:

Daily Energy Impact = daily hours of excess usage * equipment electrical demand

Required Inputs:

- Period that fault has existed
- Equipment electrical demand (name plate or monitored value)

Table 5 lists each of the algorithm-based impacts, a description of the fault, and the method to use to determine the Time and Demand to use in the above equation.

Table 5. Algorithm-based impacts

#	Fault	Time (hr)	Demand (kW)
C-3	The chiller is on when it should be off.	(Daily scheduled operating time) – (actual daily operating time)	Average measured demand over period of excess chiller run time
C-7	The condenser fan is on while the compressor is off.	(Daily fan run time) – (daily compressor run time)	Measured fan demand. If not available, use nameplate demand
C-10	The condenser pump is turning on too much in advance of the compressor.	(Daily condenser pump run time – Daily compressor run time – (Number of times compressor cycled on in day)* (condenser pump time delay)	Measured pump demand. If not available, use nameplate demand
ChWL-1	This chilled water pump is being operated unnecessarily and is wasting energy. The chilled water pump should not operate unless at least one of the supply fans in an air handling unit served by the chilled water pump is on.	(Daily CHW pump run time) – (Daily supply fan run time)	Measured CHW pump demand. If not available, use nameplate demand.
ChWL-3	The secondary chilled water pump and some of the supply fans that are served by it are not interlocked properly. This secondary chilled water pump is operating unnecessarily when all supply fans it serves are off.	(Daily secondary CHW pump run time) – (Daily supply fan run time)	Measured secondary CHW pump electrical demand. If not available, use nameplate demand. Note: If VSD is used, measured fan demand must be used.
ChWL-4	The secondary chilled water pumps that are on are wasting energy. Secondary chilled water pumps should only operate when the primary CHW pump is operating.	(Daily secondary CHW pump run time) – (Daily primary CHW pump run time)	Measured secondary CHW pump electrical demand. If not available, use nameplate demand. Note: If VSD is used, measured fan demand must be used.
ChWL-9	The compressor is not properly interlocked with the primary chilled water pumps. The primary chilled water pumps are cycling on too much in advance of the compressor.	(Daily primary CHW pump run time – Daily compressor run time – (Number of times compressor cycled on in day)* (primary CHW pump time delay)	Measured primary CHW pump electrical demand. If not available, use nameplate demand. Note: If VSD is used, measured fan demand must be used.

4.0 Discussion and Conclusions

The previous sections have provided a way of calculating the impacts associated with various faults. Most of the faults are non-interactive, or directly sum with the impacts of other faults, i.e., when multiple components are operating unnecessarily, their energy impacts all increase the overall consumption of the building. However, temperature related faults can have inverse impacts, i.e., lowering the cooling tower sump temperature will increase cooling tower fan energy consumption, but decrease chiller energy consumption. This section examines the relative impacts of the faults evaluated in the previous sections.

Table 6 lists typical electrical demands for the chiller, cooling tower, and associated circulation pumps for a 250,000 square foot office building. These values will be used to calculate the relative impacts of these faults.

Table 6. High-rise office building cooling plant electrical demand

End Use	Demand (kW)	Normalized Demand (W/SF)	Normalized Demand (kW/ton)	Percent of Total Demand (%)
Chiller (620 tons)	420.49	1.68	0.68	83%
Cooling Tower Fan	27.55	0.11	0.04	5%
Chilled Water Pumps	31.57	0.13	0.05	6%
Condenser Water Pumps	25.77	0.10	0.04	5%
Total	505.38	2.02	0.81	100%

Since impacts associated with the chiller and cooling tower are interactive, their overall impact should be evaluated. For example, faults CT-3 and CT-4 are associated with the cooling tower sump temperature being above or below the set point. If the sump temperature is above the set point, the cooling tower fan energy is reduced, but the chiller energy is increased.

Table 7 lists the magnitude of the temperature-related impacts for a one degree variation in the subject temperature. For example, if the CHW supply temperature is lower than the CHW set point by 1° F (fault C-2), the average demand of the entire cooling plant (the sum of the chiller, cooling tower fans, and circulation pumps) will increase by 0.94 percent.

The impacts for faults CT-3 and CT-4 illustrate the interactive effects of changes in the cooling tower sump temperature. Over a wide range of ambient wet bulb temperature, every one degree Fahrenheit increase in the cooling tower sump temperature results in a net demand increase of the chiller plus the cooling tower fans of 0.6 percent. Since these impacts are dependent on the average wet bulb temperature, the results are also shown in Figure 7.

Table 7. Magnitude of Electrical Impact

Fault ID	Description	End Use	Average Chiller Impact (kW/ton)	Average Cooling Tower Fan Impact (kW/ton-°F)	Average Net Impact (kW/ton-°F)	Average Percent of Net Cooling Plant Demand
C-1	CHW Supply Temperature greater than set point	Chiller	-0.009		**-0.009**	**-1.10%**
C-2	CHW Supply Temperature less than set point	Chiller	0.008		**0.008**	**0.94%**
CT-3	Cooling Tower Sump Temperature greater than set point	Chiller	0.008			
		Cooling Tower Fan		-0.003	**0.005**	**0.63%**
CT-4	Cooling Tower Sump Temperature less than set point	Chiller	-0.008			
		Cooling Tower Fan		0.005	**-0.004**	**-0.45%**

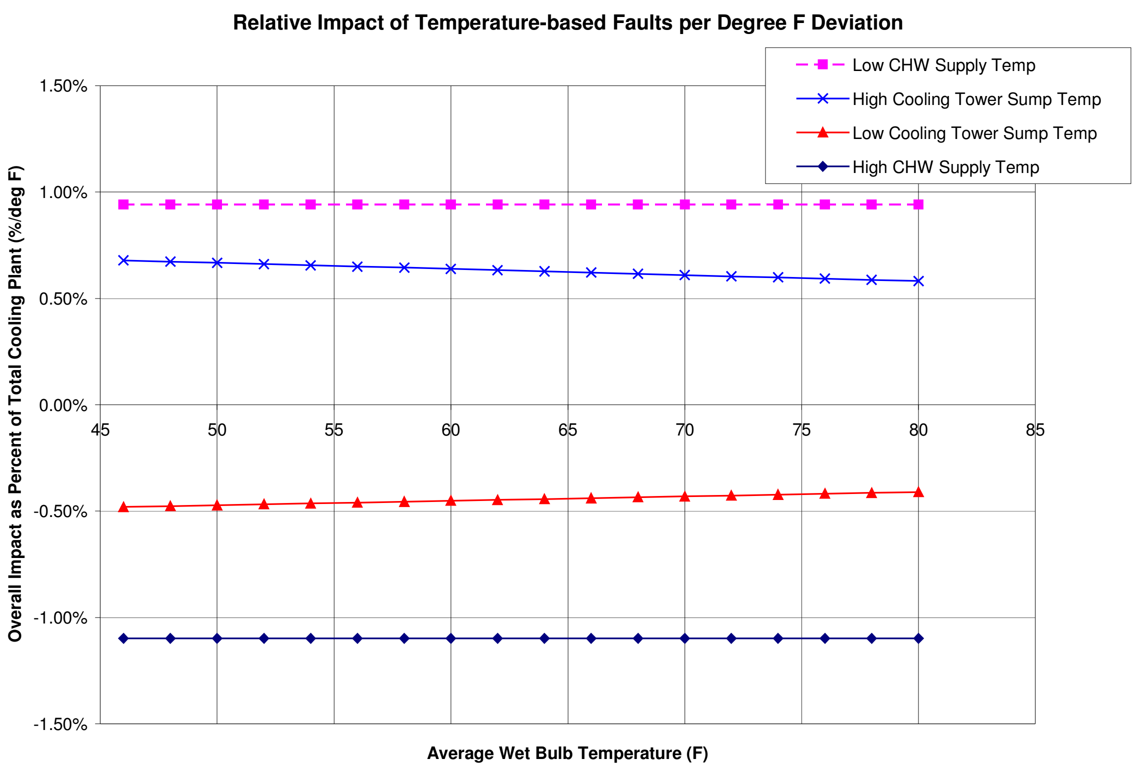

Figure 7. Relative impact of temperature-based faults

Some so-called faults can actually decrease energy consumption. If the sump temperature is lower than the set point (Fault CT-4), the net result is a reduction in overall consumption. Similarly, increasing the CHW supply temperature (Fault C-1) can also reduce energy consumption for the cooling plant. However, increasing the CHW supply temperature could have undesired effects such as less effective humidity control and potential increases in supply fan energy consumption, which were not the subject of this study.

Other faults are associated with equipment running longer than necessary. These are shown in Table 8, along with the temperature-related impacts shown above, but for a 4°F temperature deviation. The impact associated with equipment running longer than necessary is very significant. For example, the impact of excess chiller operation is on the order of 20 times greater than an increase in the cooling tower sump temperature of 4°F, for the same time period. Unnecessary pump and fan operation is also greater than any of the temperature-related faults.

Table 8. Relative impacts

#	Fault	Energy Consumption for one hour of fault operation (kWh/ton)
C-3	Chiller running longer than necessary	0.68
C-7	The condenser fan running unnecessarily.	0.08
C-10	Condenser pump turning on too early and running unnecessarily.	0.04
ChWL-1 ChWl-9	This chilled water pump is being operated unnecessarily	0.05
ChWL-3 ChWL-4	The secondary chilled water pump is operating unnecessarily when all supply fans it serves are off.	0.05
C-1	CHW Supply Temperature 4°F greater than set point	-0.036
C-2	CHW Supply Temperature 4°F less than set point	0.032
CT-3	Cooling Tower Sump Temperature 4 °F greater than set point	0.020
CT-4	Cooling Tower Sump Temperature 4 °F less than set point	-0.016

Although the magnitude of one hour of unnecessary equipment operation is greater than the magnitude of one hour of any of the temperature-related faults, it isn't clear that both of these fault categories would exist for the same length of time. It is possible that the temperature-related faults could exist for a much longer period of time since they are more subtle; equipment running when it isn't supposed to be on is more likely to be noticed than increased sump temperature that can quietly exist for weeks, if not years. With this in mind, the long-term benefits of identifying and correcting temperature-based faults can be as significant, or potentially more significant, than detecting unnecessary equipment operation.